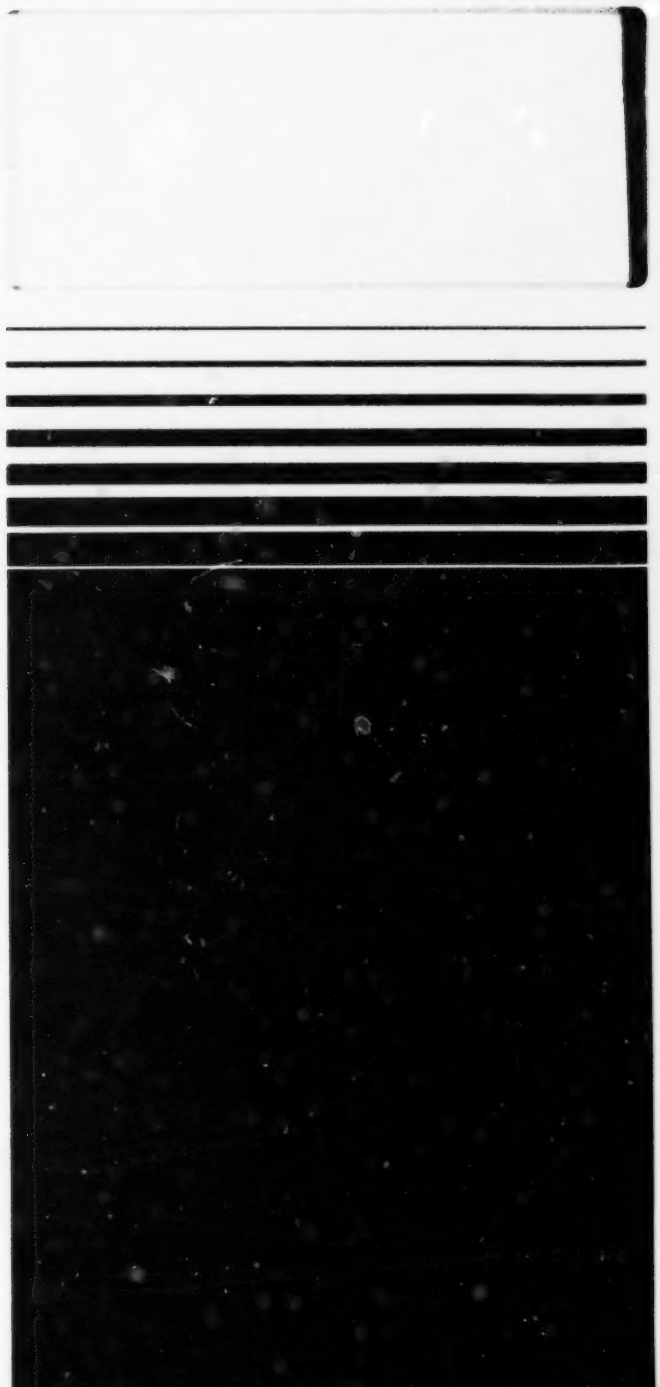
# Report Rapport

Atomic Energy Control Board

Commission de contrôle de l'énergie atomique



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# AN APPROACH TO THE CALCULATION OF DOSE COMMITMENT ARISING FROM DIFFERENT METHODS FOR THE LONG-TERM MANAGEMENT OF URANIUM MILL TAILINGS

Summary Report

A research report prepared for the
Atomic Energy Control Board by

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**RESEARCH REPORT**

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Les opinions exprimées dans ce rapport sont celles des auteurs et n'engagent pas la Commission de contrôle de l'énergie atomique.

The opinions expressed in this report are those of the authors and do not necessarily reflect those of the Atomic Energy Control Board.

# AN APPROACH TO THE CALCULATION OF DOSE COMMITMENT ARISING FROM DIFFERENT METHODS FOR THE LONG-TERM MANAGEMENT OF URANIUM MILL TAILINGS

## ABSTRACT

This report describes the development and use of a diagnostic model designed to improve our understanding of the release of radionuclides to the natural environment from uranium mill tailings management areas.

The study first developed the characteristics of a hypothetical tailings management area such that a variety of management alternatives could be studied using simulation modelling techniques. Factors describing climate and the surrounding environment were fixed and the simulation model was run to predict releases from the tailings site over time periods of thousands of years. Simulation runs were carried out for a series of six major management alternatives ranging from old abandoned practices through currently accepted practices to as yet to be proven management techniques.

This summary report describes the major aspects of the diagnostic model and the findings obtained through its use. The report does not attempt to predict doses or radionuclide dispersal patterns for any specific site, existing or planned. A more complete technical discussion of the model may be found in the two technical appendices which accompany this report.

The results of the study for the hypothetical site and for the assumptions made, that

- the dose rates to the critical groups, in the six cases studied, ranged from a small fraction of the dose limit for members of the public to a level approaching the dose limit.

- permanent flooding of the tailings significantly reduces the dose rate to the critical group.

- removal of 90 percent of uranium and thorium daughters mobilized during the acid leach process reduces the global collective dose commitment by a comparible amount.

- only a small fraction of the global collective dose commitment arises from individual dose rates greater than 1 microrem per year.

Sensitivity analyses carried out as part of this study suggest that there are several areas in which better data and a clearer understanding of process mechanisms are essential.

APPROCHE DU CALCUL DE L'ENGAGEMENT DE DOSE À PARTIR DE DIFFÉRENTES MÉTHODES DE GESTION À LONG TERME DES RÉSIDUS DES USINES DE CONCENTRATION D'URANIUM


RÉSUMÉ

Le présent rapport décrit la mise au point et l'utilisation d'un modèle diagnostique conçu pour améliorer les méthodes de prévision de rejet dans l'environnement de radionucléides en provenance des sites de gestion de résidus des usines de concentration d'uranium.

L'étude a d'abord établi les caractéristiques d'une aire de gestion hypothétique de résidus de telle façon qu'il soit possible d'étudier diverses méthodes de gestion en utilisant des techniques de simulation. Des facteurs comme le climat et les caractéristiques du milieu ambiant ont été fixés et le modèle de simulation a été passé en machine pour prévoir les rejets provenant du site de gestion des résidus pour des périodes de plusieurs milliers d'années. On a soumis à l'ordinateur six possibilités importantes de gestion, allant des techniques abandonnées jusqu'à celles qui restent à éprouver, en passant par les pratiques courantes acceptées.

Le présent rapport sommaire décrit les aspects importants du modèle diagnostique et les résultants auxquels il a donné lieu. Le rapport n'a pas pour but de prévoir des doses de rayonnement ou des modes de dispersion des radionucléides pour aucun site en particulier, existant ou prévu. Les deux annexes du rapport abordent plus en profondeur le côté technique des modèles utilisés.

Les résultants de l'étude laissent entendre, dans le cas du site hypothétique et selon les suppositions, que

- les débits de dose aux groupes critiques, dans les six cas étudiés, variaient entre une petite fraction de la limite de dose aux membres du public et un niveau proche de la limite de dose;

- la submersion constante des résidus réduit le débit de dose au groupe critique de façon sensible;

- l'enlèvement de 90% des produits de filiation de l'uranium et du thorium mis en mouvement par la lixiviation acide réduit l'engagement de dose collectif global d'une quantité comparable;

- les débits de dose individuels supérieurs à 1 microrem par année représentent seulement une petite fraction de l'engagement de dose collectif global.

Les analyses de sensibilité menées dans le cadre de la présente étude laissent penser qu'il existe plusieurs domaines où de meilleures données et une meilleure compréhension des mécanismes fonctionnels sont capitales.

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## 1.0 STUDY DEFINITION

**Overview:** This section provides a brief overview of the study and its origin. Important model components and findings ar described in this, the Summary Report. Full technical details of the study are given in the two Technical Appendices which accompany this report. The Appendices describe the Aquatic modelling process and the Atmospheric modelling process.

### 1.1 Purpose and Objectives of Study

**Purpose:** To develop methods of predicting radionuclide dispersion patterns, and consequent radiation dose impacts, resulting from disposal strategies for Uranium mill tailings.

**Objectives:** Three objectives were defined for the study.

1. To formulate a methodology for relating the quantity of radioisotopes transported from a uranium mill tailings mass to the ionizing radiation dose received by humans through atmospheric and aquatic pathways.

2. To test whether significant dose commitment differences due to alternative engineering control options are discernible.

3. To provide ways of testing the capabilities and limits of this methodology for making dose commitment calculations.

### 1.2 Origin of Study

A need became apparent in recent years for methods of assessing the effects of strategies used managing Uranium mill tailings masses.

It had become known that the behaviour of tailings masses changes with time. The nature and speed of the changes could not be confidently predicted, nor could the resulting changes in public dose impact. It was, therefore, difficult to assess the effects of tailings management strategies, since their long-term effects were not fully understood.

These difficulties in assessing long-term effects meant that the ALARA principle could not be practically applied to tailings management strategy. This study was performed in order to help reduce the uncertainties in assessing long-term effects.

### 1.3 Methodology Outline

To meet the study objectives, advances in understanding were required in three areas:

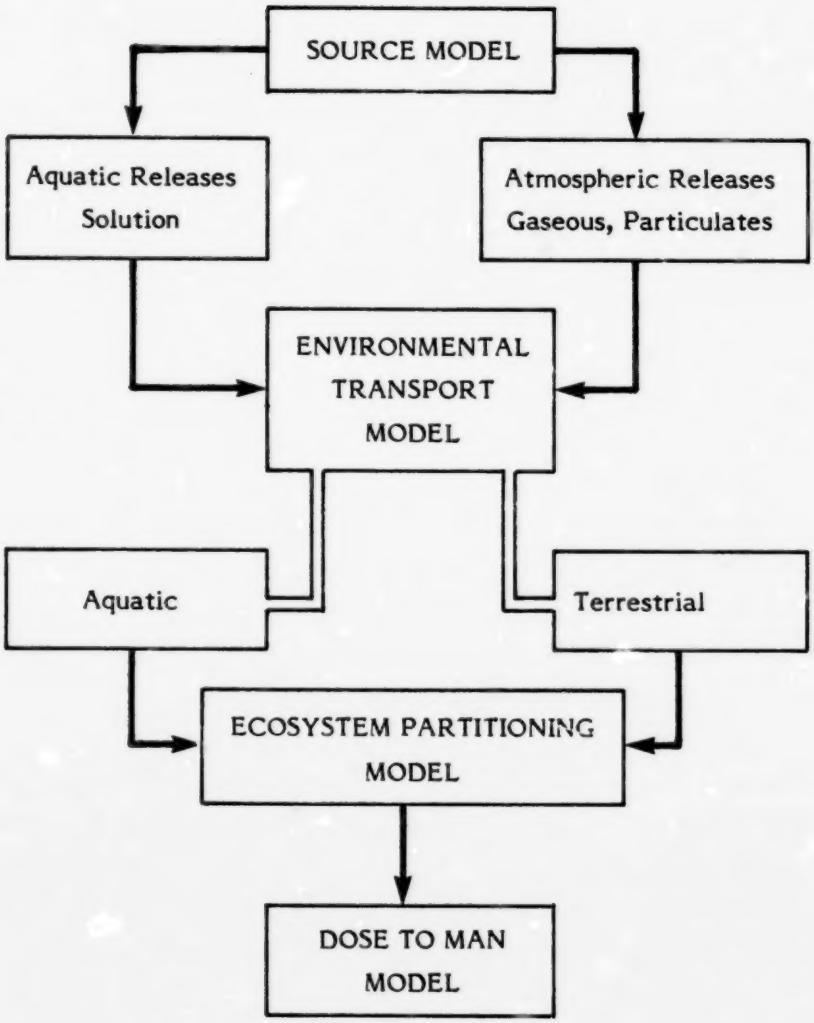
- the long-term behaviour of the physical structure of the tailings mass and its interaction with air and water;
- the long-term behaviour of contaminants within the tailings pile and their interactions with air and water. These will govern the potential rate of release;
- the processes which govern the transport of contaminants through the open environment, and the pathways through which they may affect the biosphere and man.

To gain these advances, the study investigated the behaviour of an hypothetical tailings mass. The tailings mass was assumed to interact with the northern hemisphere via its local environment. The paths of radionuclides originating in the tailings were then followed. The local environment is synthetic; it was compiled from data taken from northern Ontario.

The investigations were performed using a comprehensive, integrated model developed specifically for this purpose. The model is called the **Loading-Dosimetry model.**

The Loading-Dosimetry model may be considered to consist of four sub-models. The sub-models are:

FIGURE 1-1: **STRUCTURE OF LOADING-DOSIMETRY MODEL**



1. **the loading model,** describing the geochemical control within, and the annual flux of radioisotopes from the tailings over time;

2. **the aquatic and atmospheric transport model** which predicts respectively the concentration of all radioisotopes in all lakes and the North Atlantic Ocean, and the air and ground concentration of all radioisotopes within an 80 km radius of the hypothetical site;

3. **the population exposure model** which calculates the exposure rates of the different population groups from internal and external exposure pathways; and

4. **the dosimetry model** which calculates the quantity of ionizing radiation received by the different population groups given their exposure rates to the various radioisotopes.

Figure 1-1 illustrates the structure of the Loading Dosimetry model. The model was designed so that calculated data could be extracted at every significant stage of computation.

A sensitivity analysis was performed, after the model had been developed. The sensitivity analysis was done by changing certain coefficients and parameters affecting radionuclide transport and dose impact. After each change in any one parameter, fresh estimates of radionuclide dispersion and dose impact were made. These were used to evaluate the effects of variations in coefficients and parameters, in each of the six tailings management cases studied (see 1.4 below).

## 1.4 Important Study Parameters

The study was constrained by the important parameters summarized below. The parameters were selected to make the study as meaningful as possible.

**Tailings Mass:** 4.2 million tonnes of tailings behind a dam in an alluvial valley. Tailings surface area 40 ha, depth 10 m. Tailings composition representative of tailings from Ontario Uranium mills.

**Location:** Tailings mass located near a small 'receiving' lake in northern Ontario. All runoff and seepage enters receiving lake.

**Radionuclide Dispersion Paths:** (a) Aquatic - System of lakes and rivers originating at receiving lake; includes Great Lakes, North Atlantic Ocean, and connecting waterways. (b) Atmospheric - for Radon dispersion, entire northern hemisphere, via local area; for particulates, to 80 km radius from tailings site.

**Time Period Studied:** 10,000 years beginning with close out of tailings mass.

**Population Groups:**
- Critical group (on receiving lake)
- Local Watershed group (downstream of receiving lake)
- Local group (not including local watershed group)
- Great Lakes group
- North Atlantic Region group
- Northern hemisphere population (for airborne Radon)

**Doses Calculated:**
- Annual doses to critical group
- Cumulative global dose commitments

**Radionuclides Considered:**
- The U-238 decay series
- The Th-232 decay series

**Exposure Mechanisms:**
- Food chain, including water intake (for internal doses)
- Airborne gases and particulates (for internal and external doses
- Aqueous radionuclides, both dissolved and adsorbed on particulate matter (for external doses)

**Hydrology for Local Aquatic System:** Serpent River system (from Ontario Ministry of the Environment).

**Meteorological Data for Local Atmospheric System:** Sudbury area (from Atmospheric Environment Service).

**Tailings Management Strategies Studies:** Six related management strategies were studied, known as Cases 1 through 6:

1. Bare tailings accumulated behind porous dam - **Case 1.**
2. Tailings covered with vegetation layer, behind porous dam - **Case 2.**
3. Bare tailings accumulated behind impervious dam - **Case 3.**
4. Remove 90% of leachable Radium and Thorium from tailings before discharge from mill; then study disposal using strategies 1, 2 and 3 above - **Cases 4, 5, and 6.**

# 2.0 RESULTS OF STUDY

## 2.1 Achievement of Objectives

The study is considered to have achieved its objectives. Demonstration of achievement is outlined below.

**Objective 1:** To formulate a methodology for relating the quantity of radionuclides transported from a uranium mill tailings mass, to the ionizing radiation dose received by humans through atmospheric and aquatic pathways.

This was achieved by development of the Loading-Dosimetry model.

Field verification of the model's estimates was not part of the study. Available data suggests that predictions of radionuclide concentrations are comparable with those found within the natural environment near existing tailings sites. This indicates that no serious flaws exist in the model or its assumptions.

**Objective 2:** To test whether significant dose commitment differences due to alternative engineering control options are discernible.

Differences in dose impact are clearly discernible for different tailings management strategies assumed. These are described in Section 7.0 and highlighted in Section 2.2 below.

**Objective 3:** To provide ways of testing the capabilities and limits of this methodology for making dose commitment calculations.

This was achieved by appropriate model design. The model provides a wide variety of data from its intermediate computation stages. These data include physical, chemical, and radiological conditions at different elapsed times, and in the various components of the environment.

The model is constructed to permit the performing of sensitivity analyses. Sensitivity analyses draw attention to parameters which, if influenced, may have significant effects

on dose impact. Such analyses also indicate whether work should be done to improve the accuracy of poorly known parameters.

## 2.2 Estimated Dose Impacts Summary

The listings below allow a gross comparison of the dose impacts for the different management strategies. More detail is contained in Section 7.0 of this report, and in the Technical Appendices.

**Case 1: Bare Tailings - porous dam**

**Critical Group Dose Rates:** The dose rate peaks at about 450 mrem/a around year 200 and diminishes to near zero after 425 years. For the Years 25-175, the dose rate fluctuates near 200 mrem/a. For the Years 190-390, the dose rate remains near 350 mrem/a. Doses calculated are mostly internal, from food intake of fish and consequently highly dependent upon critical group food intake.

**Collective Committed Doses:** Global Aquatic dose rises to 200,000 man-rem after 500 years, reaching about 210,000 at year 1000. Global radon dose rises to 130,000 man-rem after 1,000 years.

**Case 2: Vegetation Cover on Tailings - porous dam**

**Critical Group Dose Rates:** A maximum dose rate of about 330 mrem/a occurs around year 400. This diminishes to near zero after 475 years. During the period 0-150 years, the dose rate is near 130 mrem/a. From Year 200-420, the dose rate is close to 300 mrem/a.

**Collective Committed Doses:** Global Aquatic dose rises to 200,000 man-rem after 500 years. A small steady rise occurs to 210,000 man-rem at year 1000. Global radon dose rises to 180,000 man-rem after 1000 years.

**Case 3: Bare Tailings - impervious dam**

**Critical Group Dose Rate:** This rises asymptotically to 23 mrem/a after 6500 years, then rapid decline occurs to near zero at year 7000.

**Collective Committed Doses:** The Global Aquatic dose rises to nearly 250,000 man-rem at year 6500, and stablizes. A 250,000 man-rem collective committed dose is reached at year 10,000. The Global radon dose rises to 3500 man-rem at year 1000.

**Case 4: Base Tailings - porous dam - Ra, Th removal**

**Critical Group Dose Rate:** This peaks at about 120 mrem/a around year 30. For the most part, the dose rate is less than 40 mrem/a for years 0-400. It then drops to near zero at year 400.

**Collective Committed Doses:** The Global Aquatic dose reaches 25,000 man-rem at year 500, then shows no further increase. The Global radon dose reaches 20,000 man-rem after 1000 years.

**Case 5: Vegetation Cover on Tailings - porous dam - Ra, Th removal**

**Critical Group Dose Rate:** A peak dose rate of about 70 mrem/a occurs around year 25. The dose rate is then less than 30 mrem/a for several hundred years. It drops to near zero at year 450.

**Collective Committed Doses:** The Global Aquatic dose reaches 23,000 man-rem at 500 years, increasing little thereafter. The Global Radon dose reaches 20,000 man-rem after 1000 years.

**Case 6: Bare Tailings - impervious dam - Ra, Th removal**

**Critical Group Dose Rate:** The dose rate peaks at near 10 mrem/a during years 0-100. It remains below 3 mrem/a during years 400-7000. The dose rate is near zero at year 7000.

**Committed Collective Doses:** The Global Aquatic dose reaches 24,000 man-rem in 5000 years, reaching 27,000 man-rem at year 10,000. Global Radon dose reaches 420 man-rem after 1000 years.

## 2.3 Study Outputs

The study produced outputs from development, computed data, and reports. These are described below.

**Development Outputs:**

- Analyses and data compilations required to build the diagnostic Loading-Dosimetry model.
- A set of quantified tailings management strategies.
- The Loading-Dosimetry model (see 1.3 above). This model provides a framework in which to evaluate the radiation detriment. Doses can be calculated for specific radionuclides and pathways. Collective doses can be calculated for discrete ranges of individual exposure rates.

**Computed Outputs**

For each of the six tailings management cases studied, the Loading-Dosimetry model was used to provide:

- an estimate of aquatic and atmospheric release rates of radionuclides over time;
- an estimate of the spatial distribution of these radionuclides in a number of environmental compartments;
- an estimate of the uptake of radionuclides into a variety of biological systems including man;
- an estimate of the radiation detriment to individuals and population groups as a result of exposure to these radionuclides.

**Reports Produced**

- This Summary Report.
- A detailed report on atmospheric dispersion of radionuclides from the tailings mass. Report title: "Atmospheric Dispersion of Radionuclides from Uranium Mill Tailings Disposal Sites". For brevity, this report is known as the "Atmospheric Technical Appendix".
- A detailed report on aquatic dispersion of radionuclides from the tailings mass. Report title: "An Approach to the Calculation of Dose Commitment Arising From Different Methods for the Long-Term Management of Uranium Mill Tailings Through Aquatic Pathways". For brevity, this report is known as the "Aquatic Technical Appendix".

## 3.0 REFERENCE TAILINGS SITE AND MANAGEMENT STRATEGIES

This section defines the hypothetical tailings site, and describes its behaviour. It also describes the various tailings management strategies evaluated in the study. The assumptions used are described. The way in which each strategy affects radionuclide transport is summarized.

It must be emphasized that the management strategies selected, and the clear-cut assumptions that are made for these strategies only, illustrate **trends** associated with the reference site specified. The field behaviour of a real site will not be so well defined. Many of the variables held constant in our model through time (such as retaining dam permeability, and presence or absence of vegetation cover) may reasonably be expected to vary. The geochemical theory being evaluated in this diagnostic model states that elements such as radium, which are included in mineral matrices such as gypsum, are released into pore water solution upon the dissolution of the mineral matrix. No allowance has been made for secondary precipitation reactions nor retardation in groundwater flow systems.

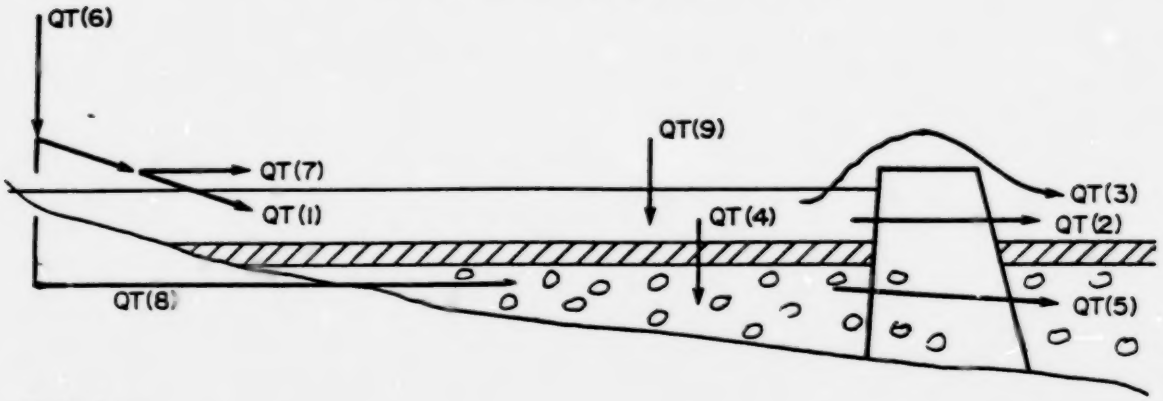
### 3.1 Reference Tailings Site Description

**Reference Site.** Figure 3-1 shows the reference site. The site contains 4.2 million tonnes of tailings with an area of 40 ha and an average depth of 10 m, contained behind a valley dam. Under the tailings is a one meter peat layer, and below that an alluvial valley floor. The catchment area upstream of the valley dam is 160 ha. Groundwater inflow from the catchment to the tailings area and outflow from the dam are considered by the aquatic model. Annual precipitation in the area is 80 cm/year; the effective yield from the drainage basin is 26 cm/year. The entire 40 ha tailings surface area is considered available for atmospheric release of particulates and radon gas.

This site and its characteristics do not correspond directly to any existing or planned site, but rather incorporate a composite of variables from many older sites.

**Reference Tailings.** The tailings characteristics chosen are listed in Table 3-1. They are based on characteristics of tailings from standard acid-leach milling techniques used in Canada, and on observations made upon actual abandoned tailings sites.

FIGURE 3-1: SCHEMATIC CROSS-SECTION OF THE REFERENCE TAILINGS SITE




Hydrology

| Case | Description | Flow Rate ($10^5$ $m^3$/yr) QT(1) | QT(2) | QT(3) | QT(4) | QT(5) | QT(6) | QT(7) | QT(8) | QT(9) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Porous dam | 3.96 | 5.49 | 0 | .072 | .336 | 4.22 | 0 | .264 | 1.6 |
| 2 | Porous dam and vegetation | 3.96 | 4.95 | 0 | .072 | .336 | 4.22 | 0 | .264 | 1.06 |
| 3 | Impermeable dam | 0 | .0003 | 4.22 | -.264 | .0003 | 4.22 | 3.96 | .264 | 0 |

QT(1) - net infiltration into tailings from precipitation onto catchment.

QT(2) - net seepage through the retaining dam.

QT(3) - surface flow over the dam not passing through the tailings.

QT(4) - seepage from tailings entering underlying alluvial deposits.

QT(5) - seepage through valley alluvial material into receiving waters

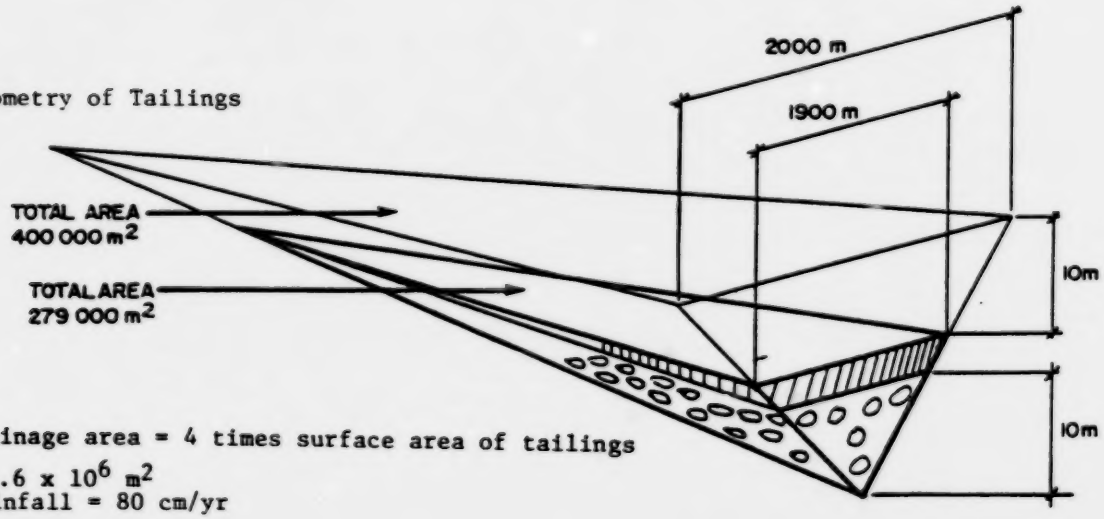
QT(6) - precipitation onto tailings catchment area.

QT(7) - surface flow from catchment over tailings.

QT(8) - seepage from catchment groundwater into alluvium underlying tailings.

QT(9) - net infiltration into tailings from precipitation onto surface of tailings.

Geometry of Tailings




Drainage area = 4 times surface area of tailings

= $1.6 \times 10^6$ $m^2$

Rainfall = 80 cm/yr

TABLE 3-1: SUMMARY OF TAILINGS COMPOSITION

| Material | Quantity |
|---|---|
| 1. Solid | |
| Gypsum | 545 M/t |
| Ca occurring as (OH, $CO_3$) | 116 M/t |
| Jarosite | 2 M/t |
| (Ba, Ra) occurring as $SO_4$ | 0.5 M/t |
| 2. Radioisotope Concentration Associated with Gypsum or Jarosite | |
| U-238 | 21 g/t |
| U-234 | $1.1 \times 10^{-3}$ g/t |
| Th-230 | $1.65 \times 10^{-2}$ g/t |
| Ra-226 | $3.22 \times 10^{-4}$ g/t |
| Pb-210 | $4.2 \times 10^{-6}$ g/t |
| Po-210 | $7.2 \times 10^{-8}$ g/t |
| Th-232 | 178 g/t |
| Ra-228 | $7.2 \times 10^{-8}$ g/t |
| Th-228 | $2.4 \times 10^{-8}$ g/t |
| 3. Radioisotope Concentration Remaining in Host Mineral | |
| U-238 | 53 g/t |
| U-234 | $2.8 \times 10^{-3}$ g/t |
| Th-230 | $8.6 \times 10^{-4}$ g/t |
| Ra-226 | $1.7 \times 10^{-5}$ g/t |
| Pb-210 | $2.2 \times 10^{-7}$ g/t |
| Po-210 | $3.8 \times 10^{-9}$ g/t |
| Th-232 | 190 g/t |
| Ra-228 | $7.5 \times 10^{-8}$ g/t |
| Th-228 | $2.5 \times 10^{-8}$ g/t |

M/t = moles per tonne

**Key Assumptions.** Several key assumptions were made concerning radionuclide behaviour in the milling circuit. Several of these assumptions have yet to be substantiated experimentally, but the data supports their main characteristics.

1. During the acid digest of the crushed ore, 95% of the U-238 daughters and 50% of the Th-232 daughters are released from the mineral matrix in which they existed in host ore.

2. The remaining daughters of U-238 and Th-232 remain locked in a mineral matrix; they cannot be mobilized for aqueous transport from the tailings.

3. The original ore contains 6% pyrite and other iron sulfide minerals. During the milling and leaching process, 20% of the iron sulfides are dissolved, releasing ferrous iron into solution. The remaining unaltered iron sulfide makes up 5% of the tailings.

4. During the strong acid leaching conditions where ferrous iron and sulphate are present, thermodynamically stable jarosite or iron sulphate is assumed to form.

5. Of the radium mobilized in the acid-leaching pachacas, it is assumed that 50% coprecipitates within the jarosite mineral structure. Most of the other 50% is adsorbed to various surfaces; a small portion remains within the sulfate-rich leaching solution.

6. An initial Ph adjustment step during milling raises the process pH to near 2 with calcium carbonate. This precipitates $CaSO_4$ (gypsum) in which some radium is included. In a later final pH adjustment step, the milling raffinate solution is raised to pH 8 with further hydroxide and carbonate addition. This removes a high percentage of the remaining sulphate ion as $CaSO_4$. As the pH rises during this final adjustment, hydroxides of thorium, lead, and polonium are formed. They are assumed to coprecipitate in the gypsum matrix, along with soluble complexes of uranium and radium.

7. The final pH adjustment with excess lime provides a reserve buffering capacity sufficient to neutralize 116 moles of $H_2SO_4$ per tonne of tailings.

8. The deposited tailings have uniform grain size and uniform distribution of process precipitate and residual minerals. Consequently, permeabilities are uniform in all directions in the tailings. All flow has downward and horizontal components through the tailings towards a seepage creek at the toe of the dam. The relatively impermeable peat layer below the tailings mass allows little seepage through into the underlying permeable glacial sands and gravels. This is an over-simplication: in the actual field case, slimes and sands are inter-fingered. This result in heterogeneous chemical distribution, and in marked differences in spatial permeability.

9. In the tailings, radionuclides weakly and reversibly adsorb onto the surface of residual and mill formed minerals, and onto coatings of gypsum or other metal sulphates or hydroxides formed in the tailings. The adsorption coefficient assumed for all radionuclides is 1 ml/g.

The above nine assumptions and their consequences affect tailings behaviour in the various management strategies evaluated. These conditions and assumptions are more fully discussed in the Aquatic Technical Appendix.

**Source Control Processes.** In order to predict variations in release rates from the reference tailings area, it is necessary to quantify environmental process interactions with the site and tailings. Some simplifying assumptions made were:

1. The retaining valley dam and underlying alluvial sands and gravels are assumed to retain their initial chemical and physical properties throughout the time of the analyses.

2. Tailings permeability is constant and unaffected by chemical dissolution. Physical changes occur on the surface of the tailings due to wind erosion; these affect fugitive dust losses.

3. All impinging environmental controllers, such as precipitation, annual temperature regimes and winds, are held constant throughout the period of analysis.

### 3.2 Radionuclide Releases from Tailings Mass

**Leaching to Surface Waters.** The tailings are considered as a column in which pure water (catchment precipitation) is introduced at the top, infiltrates through the tailings, and percolates out of the bottom of the column. A stable water table is assumed to develop in the tailings.

**Acid Production in Tailings.** As water moves through the unsaturated zone, it forms a film around the pyrite particulates within this zone. Oxygen in the pore spaces diffuses into this film, allowing the chemical oxidation of the pyrite and bacterial oxidation of the reduced sulfide resulting in acid production. As this acidic infiltrating water moves further down through the tailings, it attains a basic pH, being neutralized by excess lime added during process neutralization. Thus, acid is produced in the surface, unsaturated zone and migrates downward where it is neutralized by residual lime not yet leached from the system. As water infiltrates, it dissolves gypsum. As the acid production and consequent neutralization of lime proceed, gypsum dissolution proceeds very slowly. It is impeded by the presence of calcium and sulfate ion dissolved from solid calcium and oxidized pyrite. Consequently, radionuclides trapped in the gypsum are released very slowly.

During the initial leaching of the tailings, the pore water remains basic near pH 7-8. At this pH, jarosite is thermodynamically unstable, so a certain fraction of the jarosite is assumed transformed to ferric hydroxide (goethite) by several reactions. The goethite retains the radium.

**Buffering Exhaustion.** When the neutralization and elution of the excess lime is complete, the basic tailing pore water becomes acidic (pH 2). The soluble calcium concentration in pore water drops, allowing an increase in gypsum solubility. Sulfate production also continues from the pyrite oxidation reactions. Dissolution of gypsum and of the iron hydroxide (goethite) occurs during acidic conditions, releasing radionuclides into the pore water. When oxidation of available pyrite is complete, no more sulfate is produced. This leaves gypsum dissolution as the only significant sulfate source. Also at this point, the tailings pH returns to modestly acidic conditions. With the exception of thorium, which is postulated to form a soluble thorium sulphate complex at pH values below 4.5, all of the radionuclides released, reversibly adsorb to the surface of residual

mineral particles. In fact, there may be other processes than reversible adsorption reactions occurring. Exhaustion of available pyrite, therefore, slows the release of radionuclides from the tailings.

**Radionuclide Release Rates.** The net result of the above is that there is a slow release of radionuclides during the basic leaching phase, followed by a more rapid release during the acid leaching phase. In addition, thorium is rapidly released during acidic conditions due to the mobilization of thorium sulfates. Upon completion of pyrite oxidation, the highest dissolution rate of gypsum occurs. After all of the process-formed gypsum is dissolved and released, along with all of the soluble thorium sulfate, the remainder of the adsorbed radionuclides are released to the pore water and seepage concentrations drop off. A graphic representation of this release sequence for radium in the base case is shown in Figure 3-2.

**Releases to the Atmosphere**

**Particulate Losses.** The tailings are subject to fugitive dust losses from the surface. Fine particulate material is more easily suspended and transported from the tailings area than is coarser material. The surface of the tailings, therefore, becomes depleted in fine particulates and the flux of particulates from the surface decreases with time. The decrease in loss rate is shown in Figure 3-3. Calculations assume a 10% surface moisture content in the tailings. After a hundred years or so, the loss of particulates stabilizes, as weathering action becomes the sole source of fine particles. In addition to changes in surface particle size distribution, their specific activity also changes. Because of vertical leaching in the tailings, the specific activity of the particulates blown from the surface decreases very rapidly. It stabilizes at about 10% of the initial value after a couple of decades.

**Radon Releases.** Much radon decays before it can be released to the tailing pore space and become available for diffusion to the atmosphere. The amount that is released from any given mineral is expressed as an emanation coefficient. These values chosen were 0.1 for residual host mineral, 0.15 for jarosite and 0.25 for gypsum. The flux of radon gas to the atmosphere decreases with time. It is eventually controlled by the radioactive decay of residual thorium-230 locked in the insoluble mineral matrix, after all of the soluble radium has been leached from the tailings pile. Figure 3-4 shows the manner in

FIGURE 3-2:

TAILINGS PORE WATER CONCENTRATION

BASE CASE - Ra-226

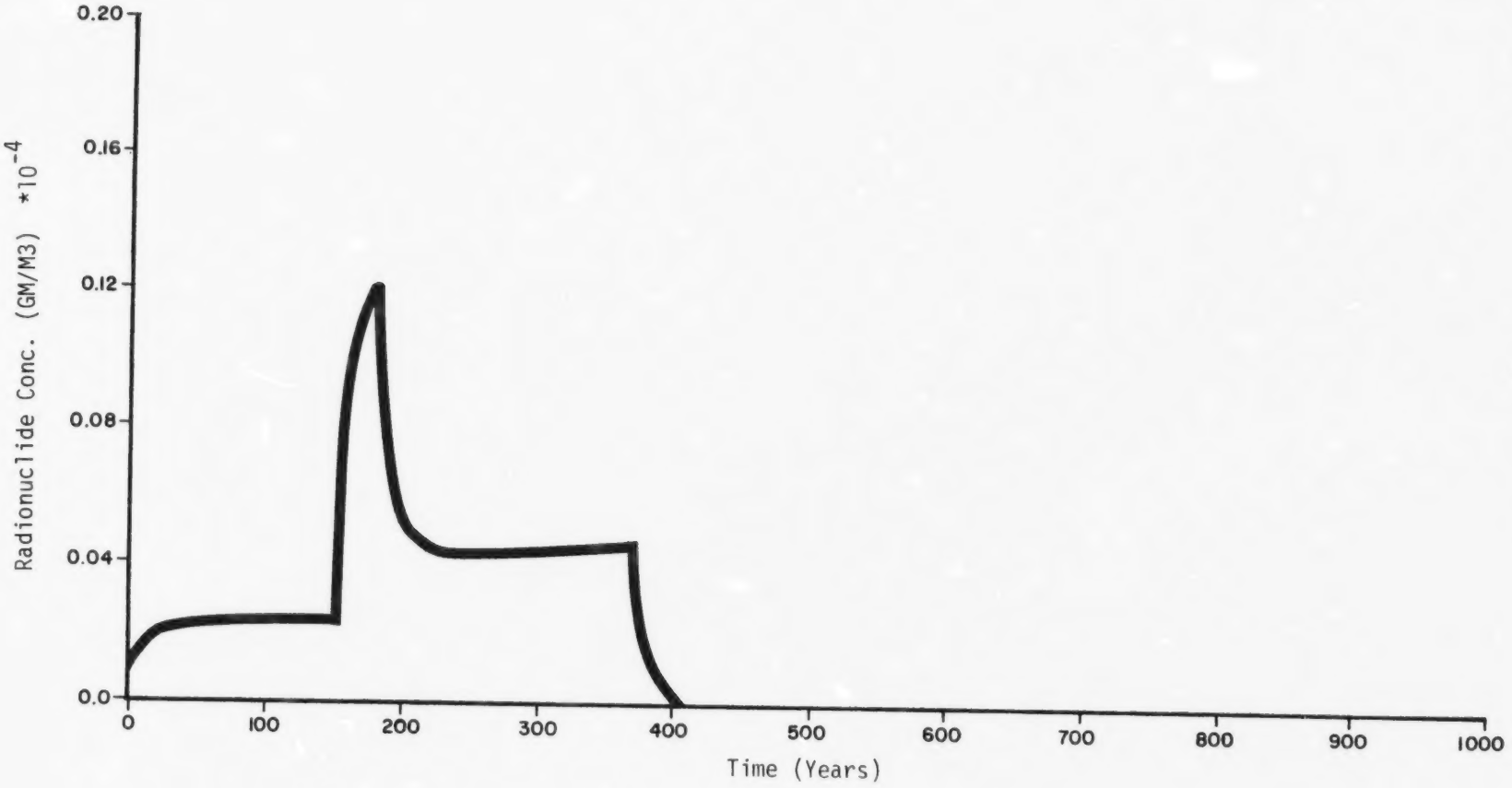


FIGURE 3-3: LOSS OF PARTICULATES FROM THE SURFACE OF THE TAILINGS AS A FUNCTION OF TIME

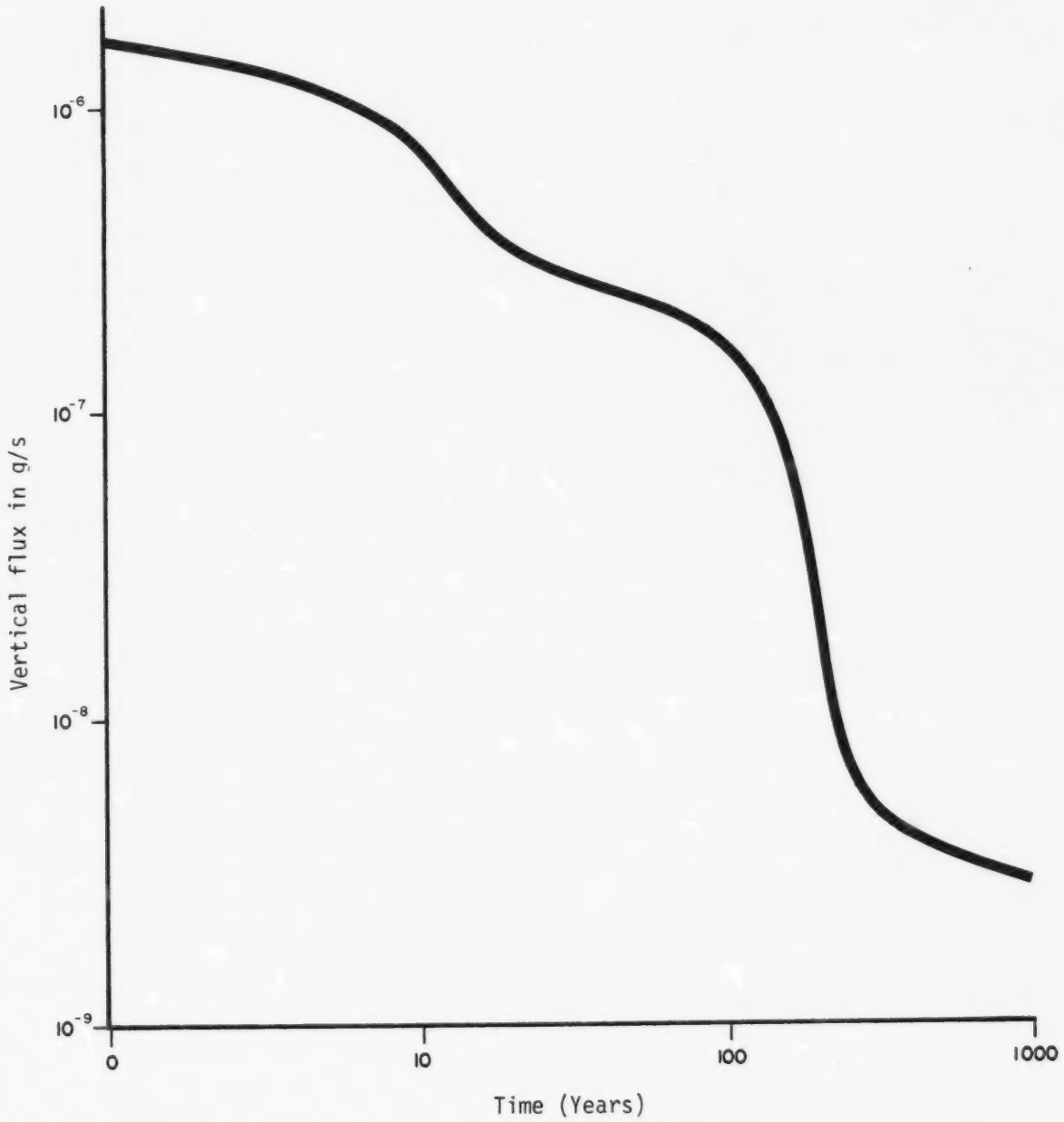
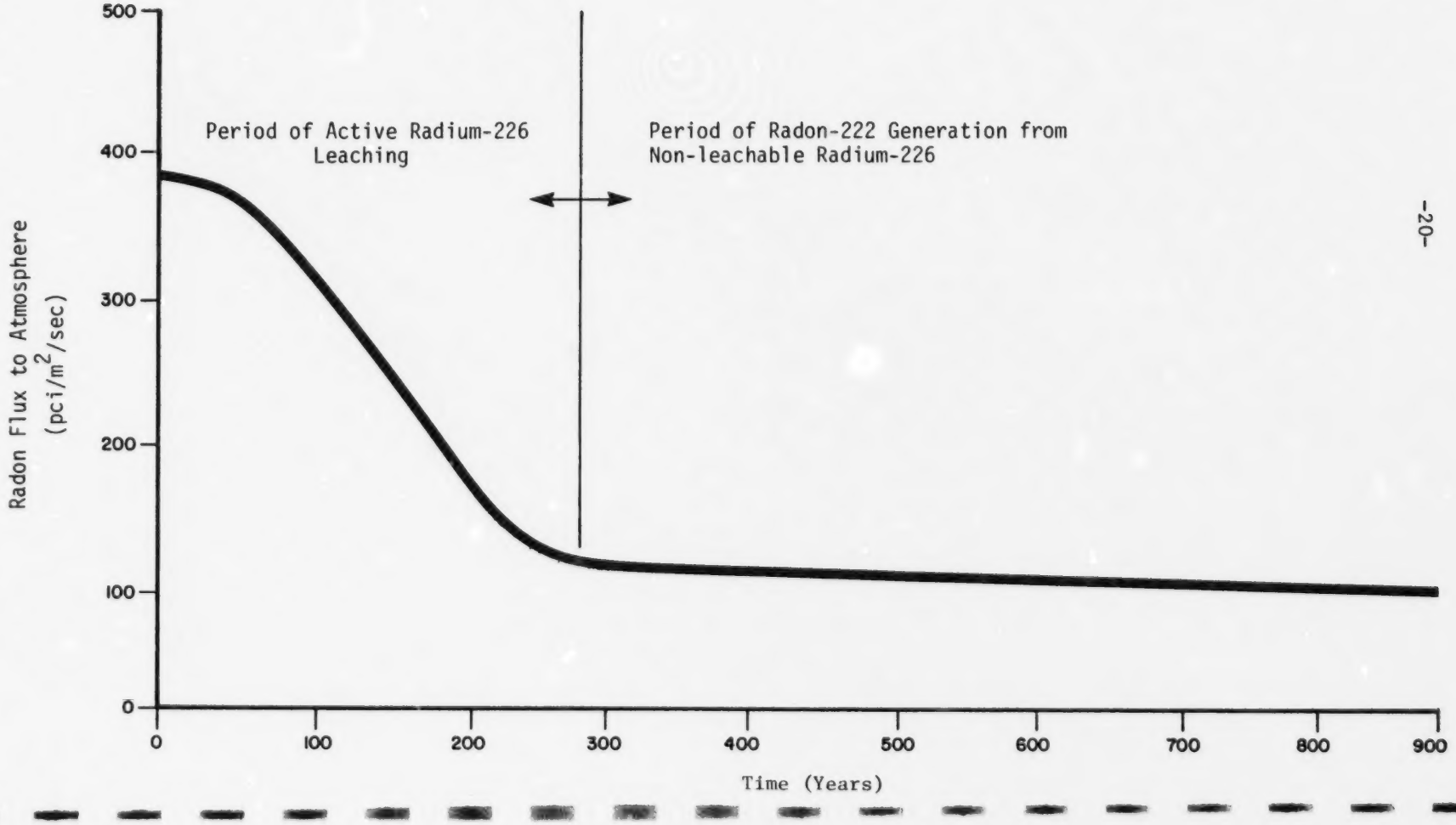


FIGURE 3-4

RADON-222 GAS RELEASE FROM THE REFERENCE TAILINGS AREA AS A FUNCTION OF TIME



which this radon flux changes with time. Both fugitive dust losses and radon gas flux show pronounced seasonal shifts. Frozen ground and snow cover restrict the radon flux and fugitive dust loss from the tailings. These seasonal changes have been blended to a yearly average for the long-term calculations carried out for this study.

### 3.3 Tailings Management Strategies

The subsection below describes the assumed engineered tailings controls, known as 'management strategies'. The purpose of such strategies is to reduce the public radiation dose impact resulting from existence of the tailings mass. All strategies are applied to the same reference tailings mass placed in the same valley as described in subsection 3.1 above. That base reference case is known as Case 1.

The effects of each management strategy are described.

#### 3.3.1 Vegetation Cover Over Reference Tailings - Case 2

A cover of native vegetation is assumed to be established on the tailings surface. The vegetation cover is self-sustaining. The surface of the tailings would be conditioned with lime and fertilizer to encourage the establishment of vegetation. Compared with the untreated reference site (Case 1, above), a vegetation cover is expected to:

1. eliminate fugitive dust losses
2. enhance radon gas exhalation
3. increase the quantity of acid production
4. decrease the rate of radionuclide leaching

**Atmospheric Losses.** The completed vegetation cover is assumed to effectively eliminate fugitive dust losses. The data is presented in this manner to allow proration between the base case and vegetated alternative if a site were to be partially vegetated. The specific activity of the surface soil is assumed to be unaltered by the addition of lime and fertilizer. The native vegetation has been assumed to increase rather than decrease the radon-222 flux to the atmosphere. The mechanism responsible for this increase is the aqueous transport of radon gas present in the tailings pore spaces to the leaves of the vegetation. Also contributing to an increase in radon flux is an

increase in the fracturing of the tailings mass due to root penetration. Increased radon flux is treated, for modeling purposes, as an increase in the emanation coefficient.

**Seepage Losses.** The transpiration of tailings pore water by vegetation alters the hydraulic balance within the tailings. The mean hydraulic flushing time of the tailings increases from 2.6 years (Case 1) to 2.8 years. This results in a slower rate of release of radionuclides to seepage water because of the solubility equilibrium that has been assumed in the tailings. The loss of transpired water also results in the lowering of the water table in the tailings. This increases the percentage of unsaturated tailings (where rapid acid production could occur) from 22% (Case 1) to 29%. In calculating rates of acid production, no allowance was made for extra lime that may have been added in order to establish a vegetative cover.

### 3.3.2 Reference Tailings Behind Low Permeability Dam - Case 3

This strategy used a low permeability dam to retain the bare reference tailings in the same (Case 1) valley. Bulk permeability of the dam is assumed reduced to $10^{-5}$ cm/s. This could be achieved by giving the dam a low permeability core, and by grouting the dam to bedrock. Compared with the reference (Case 1) dam, a low permeability dam is expected to:

1. eliminate fugitive dust losses;
2. reduce radon-222 exhalation to the atmosphere to about 1% of that observed in the base case;
3. restrict seepage volume of tailing pore water to about 5% of that in the base case;
4. slow pyrite oxidation to the point where acidic tailings pore water and acid seepage are eliminated.

**Hydrological Effects.** The most important primary effect would be a decrease in the seepage passing through the tailings. The hydraulic flushing time of tailings pore water would increase from 2.6 years (Case 1) to 53 years. This restriction of seepage results in a very much lower rate of entry of radionuclides into the receiving lake. There is consequently much more dilution, and levels of radionuclides in downstream receiving waters are much lower than in Case 1. This restriction of seepage, with unchanged

catchment inflow, causes the water table to rise to the surface of the tailings. Most runoff water from the catchment basin is now forced to flow across the top of the tailings and over the spillway on the retaining dam. A shallow marsh could, in theory, develop over most of the fully saturated tailings, depending upon the spillway elevation. It has been assumed, however, that no marsh vegetation develops, and that the water table elevation is coincident with the surface of the tailings.

**Radionuclide Losses.** Radon gas produced within the tailings mass must now diffuse through water ($D = 5 \times 10^{-6}$ cm$^2$/sec) rather than air ($D = 0.1$ cm$^2$/sec). This reduces the radon-222 exhalation rate to the atmosphere above the tailings by about 100 fold. Tailings saturation also impedes oxygen diffusion into the tailings. This restriction of oxygen movement means that the rate of pyrite oxidation in the tailings does not proceed at a significantly fast enough rate to result in the seepage becoming acidic. The low seepage rate slows the initial flush of contaminated pore water from the tailings. Consequently, the seepage from the tailings does not show any marked shifts in radionuclide concentration with time. The receiving waters do not become acidic as a result of pyrite oxidation, even in 10,000 years.

### 3.3.3 Radionuclide Removal Strategy - Cases 4, 5, and 6

This strategy is applied to the tailings before they are deposited in the tailings disposal site. It requires the extraction of uranium and thorium daughter products from the tailings. Extracted radionuclides are not sent to the tailings disposal site, but are managed in some other way. This model ignores any radiation detriment resulting from their disposal. After radionuclide extraction, the tailings are sent to the tailings site. They are there managed by one of the strategies described in Cases 1, 2, and 3 above. For study purposes, the resulting combinations of strategies are called Cases 4, 5, and 6 respectively. The consequences of management cases are summarized below, after the description of extraction parameters.

**Extraction Parameters.** The key study assumptions (3.1 above) state that 95% of U-238 daughters and 50% of Th-232 daughters are leached from the mineral matrix during milling. It is assumed here that 90% of the thorium and radium radionuclides so leached are removed from the tailings. The thorium and radium radionuclides which resisted leaching during milling are assumed untouched by this management strategy; they remain

locked in the mineral matrix. The radionuclides addressed are those which, during milling, were at some point in solution or colloidal suspension and not removed during uranium extraction. From those states, they were adsorbed on mineral particle surfaces, or incorporated in gypsum or jarosite precipitated in the tailings.

Compared with the host ore, this strategy removes 85.5% of the total Th-230 and Ra-226, and 45% of the total Th-232 and Ra-228. These radionuclides are removed from the tailings by processes described in 3.1 and 3.2 above.

**Case 4: Radionuclide Removal Applied to Case 1**

1. Specific activity of fugitive dust losses will initially be reduced 85.5% for thorium-230 and radium-226 nuclides, and 45% for thorium-232 and radium-228 nuclides. After about 100 years, fugitive dust specific activity will approximate that of the base case for the corresponding time.

2. The initial 85.5% removal of radium-226 results in a reduction of radon-222 exhalation of almost 88%. This is because 90% of the radium-226 is extracted from the gypsum and jarosite fractions with assumed emanation coefficients of 0.25 and 0.15 respectively, and none from residual minerals with an assumed emanation coefficient of 0.10. The result is a lower composite emanation coefficient.

3. The removal of thorium and radium reduces the specific activity of these isotopes in gypsum and jarosite by 90%. This reduces seepage water specific activity by a corresponding amount.

4. Acid generation potential is not affected.

**Case 5: Radionuclide Removal Applied to Case 2 (Vegetation Cover)**

1. Radon exhalation will initially be 88% less than in Case 2.

2. Seepage water specific activity will be reduced to 90% of that for Case 2 after lead and polonium isotopes decay to secular equilibrium levels.

3. Acid generation potential is not affected.

**Case 6: Radionuclide Removal Applied to Case 3 (Low Permeability Dam)**

1. Radon exhalation will initially be 88% less than in Case 3.

2. Seepage water specific activity will be reduced to 90% of that for Case 3 after the decay of lead and polonium isotopes to secular equilibrium.

3. Acid generation potential is not affected.

## 4.0 ENVIRONMENTAL RADIONUCLIDE TRANSPORT

This section describes the modeling of the main environmental systems which transport radionuclides. Some of the more important transport mechanisms are discussed.

### 4.1 Aquatic Transport Systems

The aquatic environmental pathways are the routes by which the designated radionuclides are transported through the local watershed and the Great Lakes into the Atlantic Ocean.

Radionuclides leaching from the reference tailings site are assumed to flow, without loss, through a surface creek and groundwater into a receiving lake. The receiving lake, in the diagnostic model, has been designated as Quirke Lake. It is located near the headwaters of the Serpent River system in northern Ontario, Canada. The total system considered in the aquatic hydrologic model includes the Serpent River basin down to the North Channel of Lake Huron, Lake Huron, Lake Erie, Lake Ontario and the North Atlantic Ocean. The Serpent River system is designated as the local watershed; the Great Lakes are designated as the regional watershed. This system was chosen for diagnostic modeling purposes because of the good availability of hydrological and atmospheric data.

The model "partitions" radionuclides within any given lake into a series of "compartments". The principal compartments evaluated are water, particulates in the water column, and lake sediments. It has been assumed that present water quality and biological processes operating within the lake and ocean systems are constant through the time period investigated except as affected by tailings discharges.

**Receiving Lake Water.** As the tailings seepage enters the receiving lake, it is instantaneously mixed with and assumes the general qualities of present day receiving lake water. During the initial leaching process, the pH of the receiving lake will be depressed from its initial value of 7-8 to a value of 6-7. This will result in little change in the gross chemistry of the system. As the characteristics of the tailing seepage entering the receiving lake change with time, from a high pH input (7-8) to a low pH input (2-3), the pH of the receiving lake is calculated to change from 6-7 to 4-5. Resultant chemical precipitation and dissolution processes become important in radionuclide transport.

When mixing has occurred, adsorption will occur to particulates in the water column, and uptake by fish and aquatic macrophytes is calculated. Adsorption and partitioning coefficients (known as 'transfer' coefficients) used are presented in Table 4-1. For each time step as the input loading changes, the concentrations of various radionuclides in water, water column particulates, fish and aquatic plants also change.

**Receiving Lake Sediments.** The receiving lake is assumed to have a mean depth of 37 m and a mean annual suspended particle concentration of 0.1 $mg/m^3$ in the water column. Each particle has a settling velocity of 25 m/year. These conditions result in some of the radionuclides being incorporated into shoreline beach sediments which are potential contributors to external radiation dose from shoreline exposure during the period of active radionuclide sedimentation. The major portion of the sediment, however, accumulates in the deep depositional zones of the lake where it is continually being buried by new sediment. The net result is that the surficial sediments will have a specific activity proportional to the activity of the particulates in the overlying water column. Deeper sediments will have an activity, corrected for decay, corresponding to water concentrations during the time they were deposited. The sediments themselves have been artificially split into three boxes. The surficial compartment (4 cm in the local system lakes, but which varies in depth depending upon the lake), is oxidizing in nature. The pore water concentration of radionuclides in these oxidized sediments is controlled by the burying rate and the adsorption processes typical of a saturated oxidizing environment. Below the oxidizing layer is a reduced layer, 10 cm deep, where solid-liquid adsorption processes reflect the change in oxidation/reduction potential. Radionuclides within these two compartments diffuse back into the overlying lake water. Below the 14 cm depth in local system lakes, the transport back into the overlying water becomes insignificant. Radionuclides more than 14 cm deep are assumed lost from the system.

After most of the radionuclides have been released from the tailings, natural lake and sediment processes continue. On the bottom of the lake, sediment accumulation will eventually bury contaminated sediments, eliminating transfer of radionuclides back into the overlying water column by diffusion. Similarly, shoreline erosion will continue and shore deposited radionuclides will slowly work their way into deeper lake sediments.

TABLE 4-1: SUMMARY OF FOOD CHAIN TRANSFER COEFFICIENTS
(pCi/kg per pci/l)

| | Environmental Compartment | | | | | |
|---|---|---|---|---|---|---|
| | | | Boney Fish | | | |
| Radionuclide | Water | Macrophyte (Wild Rice) | Fresh Water | Marine | Marine Shellfish | Moose |
| U-238 | 1 | 20 | 10 | 10 | 10 | 1.7 |
| U-234 | 1 | 20 | 10 | 10 | 10 | 1.7 |
| Th-230 | 1 | 30 | 30 | 10,000 | 2,000 | 1.5 |
| Ra-226 | 1 | 50 | 50 | 50 | 100 | 4.8 |
| Pb-210 | 1 | 4 | 300 | 300 | 170 | 0.33 |
| Po-210 | 1 | 40 | 50 | 3,000 | 1,600 | 2.8 |
| Th-232 | 1 | 30 | 30 | 10,000 | 2,000 | 1.5 |
| Ra-228 | 1 | 50 | 50 | 50 | 100 | 4.8 |
| Th-228 | 1 | 30 | 30 | 10,000 | 2,000 | 1.5 |

**Thorium Transport.** At a low pH (4.5), thorium is very soluble as a thorium sulfate complex, but very insoluble at pH 7-8. Accordingly, the thorium dissolved in the upper layers of the tailings is assumed to be reprecipitated in deeper tailings as a thorium hydroxide at pH 7-8. Upon the tailings pore water going acid, this thorium dissolves and migrates out to the receiving lake as a pulse, but because of the near neutral pH in the receiving lake, much of the thorium reprecipitates to the receiving lake sediments. The remainder of the thorium undergoes normal lake processes of adsorption, settling and transport downstream. Upon complete oxidation of pyrite in the unsaturated zone of the tailings, the tailings pore water pH and that of the receiving lake return to near neutral.

**Downstream Waters.** As water soluble radionuclides move out of the receiving lake, they pass through a series of lakes. In each lake, the same processes occur. Soluble radionuclides adsorb onto particulates in the water column. The contaminated particles can settle to the lake sediments, be taken up by fish and macrophytes, or contribute to beach sediment activity. The adsorption coefficients influence the partitioning between soluble and particulate phase. These may change within each lake with such things as hydraulic inflows and outflows, sedimentation rates, fish and macrophyte production, and water consumption.

In the North Atlantic Ocean, the treatment of radionuclides is somewhat different. They first enter a surface water circulation system where transfer to human exposure pathways (fish, shellfish, beach sediments) and sedimenting particulates occurs. Once a radionuclide has settled out of the surface layers (top 75 m), it enters the deeper waters. From the deep waters, it can settle to the deep sediments and be lost to the surface water circulation or be carried back to surface waters by upwelling. Circulation and sedimentation in deep ocean waters is assumed to occur in both the North and South Atlantic Oceans.

## 4.2 Atmospheric Transport Systems

The movement, in the atmosphere, of radionuclides released from the reference tailings site was modelled to determine concentrations in vegetation, soil, and the air. The emitted radionuclides included both radon-222, in a gaseous form, and particulate radionuclides contained in the dust removed from the site by wind erosion. The generation of a dust emission rate and the dispersion of the elements in the atmosphere were modelled using the UDAD (Uranium Dispersion and Dosimetry) code developed by

Argonne National Laboratories. The principles of the model are discussed in more detail in both the atmospheric Technical Appendix and the UDAD manual. Calculations using UDAD were made for a 1000-year period following closeout. UDAD predictions were not carried beyond 1000 years because a monotonic decline in release of radionuclides appeared evident.

UDAD assumes constant source terms. Since conditions in the tailings change with time, the 1000-year study period was divided into seven time steps. Source terms were fixed anew for each time step.

The UDAD code calculates:

- radon and daughter concentrations in WL
- cloud concentration (allowing for depletion)
- soil concentration

The total ground deposit, in any given time step, was determined through the use of a separate program. This algorithm summed the contribution of all previous time steps, having allowed for weathering loss and decay, and the contribution from the current time step.

Food chain and dosimetry calculations were then undertaken using the above information.

The UDAD code considers:

- wind erosion source definition
- radioactive decay allowances
- deposition/resuspension relationships
- weathering factors

The wind erosion section of the model determines the amount of material removed from the surface of the tailings. The activity of this material changes according to the geochemical conditions in the tailings. Without the ability to vary source terms with time, these varying activities require further compensating calculations to estimate the buildup of material in soil and vegetation.

Meteorological data is that of Sudbury. Ten years of hourly data were combined to provide a triple joint frequency of wind speed, wind direction, and stability class.

All material released is allowed to decay. Radon-222 decays to polonium and lead particles, which settle to the ground in a fashion similar to the other particles released from the site. The deposition terms are governed by the physical properties of size and density and related to cloud concentration. The concentration buildup on the ground is a function of deposition, but is modified by:

- weathering factors accounting for movement deeper into the soil and physical and chemical behaviour of the radionuclide;

- resuspension of material from the surface of soil and vegetation.

Resuspension is also linked to the weathering factor and, as such, only materials with long half-lives are considered for resuspension. Daughter products are assumed to add to the soil buildup concentrations.

## 5.0 POPULATION GROUP EXPOSURE PATHWAYS

This section defines the various population groups considered, and describes lifestyle and pathway factors affecting their radiation doses. General pathways are considered first. Attention is then given to group-specific pathways.

### 5.1 General Pathway Systems

#### 5.1.1 Aquatic Pathways

Foodchain and external exposure aquatic pathways are regulated by the transfer of radionuclides from the solution phase to the solid phase. This transfer may be abiotic in nature such as the adsorption onto clay or silt particles suspended in the water column. It may also be biotic, as in the case of biological uptake by algae, fish, shellfish and aquatic macrophytes. Human consumption of such biota will result in radiation doses to the consumer. In evaluating such doses, a critical pathway approach has been employed. This involves the identification from the literature of the most important aquatic foodchains leading directly or indirectly into man. Transfer coefficients are then selected from the literature for the radionuclides of the U-238 and Th-232 decay series, in freshwater and marine biological systems (see Table 4-1). The 'Aquatic' Technical Appendix provides more detail. The use of these transfer coefficients allows the direct calculation of body burdens of radionuclides in organisms such as fish, shellfish and aquatic plants which may feed directly into the diet of man.

**External Exposure:** The critical group and regional population will receive a certain dose component from external exposure. This will occur through immersion in water and walking or lying on beach sediments which contain radioactive materials.

#### 5.1.2 Atmospheric Pathways

Foodchain and external pathways in the atmospheric portion of the diagnostic model are regulated by the transfer of particulates from the atmosphere to vegetation and soils. The pathways are also regulated by the suspended particulate concentrations at ground level, caused by exposure to radon gas. The transfer of particulates to soil and vegetation surfaces is determined by particle concentration in the atmosphere and the

settling velocity of those particles. Internal exposure to radon and atmospheric particulates is determined by the atmospheric concentration and the inhalation volume of the exposed individual.

For modeling purposes, a constant settling velocity of 0.003 m/s has been assumed. A residence half-life of particulates on vegetative surfaces of 14 days has been assumed for all vegetation types. Loss of particulates from these surfaces is due to rain washoff and wind dislodgement. Mixing of settling particulates is assumed to occur within the top 10 cm of soil, and loss from this soil horizon occurs in this particular model through radioactive decay and a weathering half-life accounting for removal to deeper soil horizons.

Uptake into vegetation occurs through both root uptake from soil and transfer through leaf surfaces. Tables presenting the values used in calculating transfer to plants through both foliar and root uptake are presented in the Atmospheric Technical Appendix. For edible vegetables, the specific activity is reduced by a factor of two to allow for radioactivity loss in preparation steps such as washing, peeling, boiling, etc.

Meat and dairy products are considered as part of the food chain. The calculation of concentrations of radionuclides in cattle, dairy products, poultry and wild game is based upon three components. These include concentration in ingested food and water (pCi/kg), an average ingestion rate (kg/d), and a transfer factor from feed to meat (pCi/kg per pCi/d intake). The types of food, sources of feed and, hence, their radionuclide content, vary with the particular species investigated, be it, for instance, cattle, moose or poultry. There is a shortage of data on moose; their metabolic parameters and, hence, transfer factors were assumed to be similar to cattle.

## 5.2 Population Groups - Lifestyles and Pathway Factors

### 5.2.1 Critical Group

For the purpose of this study, an hypothetical critical group was defined as living year-round on the shore of the receiving lake about 2 km from the tailings site. This group consists of both infants and adults and has consumption patterns and living habits which would result in the maximum reasonable exposure to radionuclides released from the reference tailings site.

The most highly exposed individual within the critical group was assumed to be an adult. Calculations were also carried out for infants within the critical group. Table 5-1 summarizes their assumed consumption patterns and lifestyle habits. All drinking, bathing and washing water are assumed to come directly from the surface waters of the receiving lake.

**Food consumption:** The group is assumed to eat wild rice grown on the lake. At present, there is no evidence of wild rice being consumed in the reference area from which the hydrologic model was adapted, but it is possible that such consumption could occur over the long term. All fish consumed in their diet are assumed to be taken from the receiving lake. The moose consumed by the critical group are assumed to derive all of their drinking water and the aquatic macrophyte component of their diet from the receiving lake. Moose that are consumed from the area surrounding the receiving lake watershed are not considered to have contributed to the dose to the critical group.

**External Exposure:** This is caused by immersion (swimming or bathing in one's residence) in lake water and walking on contaminated sediments. The degree of sediment contamination is calculated by taking the specific activity of the general lake sediments and correcting them for a shoreline winnowing effect, a specified contaminated depth and a shoreline width factor.

### 5.2.2 Local Watershed Population

The local watershed population consists of about 1000 individuals living along waterways downstream of the receiving lake, and upstream of the Great Lakes. In evaluating the dose to this group, several approaches were taken.

**Water and Fish:** The population obtains all of its drinking, washing and bathing water from the system. Consumption of fish from the local downstream lakes and rivers was assumed to be 33% of the maximum sustainable yield of fish from the system. Fish production was determined for each lake in the hydrologic model based upon its surface area and present estimated maximum sustainable yields per hectare. These potential yields are based upon correlations with present day lake surface area, total dissolved solids levels, and mean depth. Corrections were made for yields changing with future

TABLE 5-1: CONSUMPTION PATTERNS AND LIFESTYLE HABITS

Table 5-1(a): AQUATIC EXPOSURE MODEL ASSUMPTIONS

| Consumption Pattern | Adult | Lifestyle Habits | Adult |
|---|---|---|---|
| Water consumption | 730 L/a | % of time water immersion | 1.3% |
| Wild rice consumption | 16 kg/a | % of time walking on contaminated beach | .68% |
| Fish consumption | 20 kg/a | % of time lying on beach | .37% |
| Moose consumption | 35 kg/a | | |

Table 5-1(b): ATMOSPHERIC EXPOSURE MODEL ASSUMPTIONS

| Consumption Pattern | Adult | Lifestyle Habits |
|---|---|---|
| Air Respiration | 8300 $m^3$/a | For external exposure and lung dose calculation, the individual is assumed to reside at the designated location year-round. The most highly exposed and average individual spend 80% of their time indoors. |
| Above Ground Vegetables | 100 kg/a | Food consumed by the critical group is assumed to be all grown or raised on pasture or grain grown at the receptor group location. |
| Below Ground Vegetables | 180 kg/a | |
| Poultry | 30 kg/a | |
| Eggs | 40 kg/a | |
| Milk | 310 kg/a | |

changes in lake water chemistry, related to acid release from the reference tailings. The group was not assumed to consume wild rice in any quantity from the affected watershed.

**Moose:** The quantity of moose consumed for each lake drainage basin in the hydrologic system modeled was related to the number of moose killed in the area, the average moose population density, and the drainage area for each lake. The radionuclide concentration in moose meat was related to the lake concentration by a bioaccumulation factor calculated by this study. This bioaccumulation factor is based upon bioaccumulation factors between macrophytes and water and the portion of the total moose diet constituted by macrophytes. The quantity of moose was then assumed to be spread throughout the local population when calculating the local watershed population dose.

Some of the fish caught in the local watershed and some of the moose shot in the area will be removed from the region. This fact is ignored. It results in calculated doses to individuals living in the local area being overestimated. Note, however, that the global collective dose component from these sources is independent of where the moose and fish are consumed.

### 5.2.3 Local Population

The local population is defined for diagnostic modeling purposes as being that group which lives within an 80 km radius of the reference site. It is separate from the local watershed population which was used for calculating aquatic doses (see 5.2.2 above). There is one large town about 15 km from the reference site and several smaller communities down along the Lake Huron shoreline. The population data (numbers and location), based upon 1981 census information, was held constant for the modeling period.

**Food:** Farming activity in the area is limited by climate and a lack of arable land, but some crops and livestock are produced. 'Above ground vegetables' (see Table 5-1(b)) for modeling purposes include wheat, oats, barley, buckwheat, peas, corn and garden vegetables. 'Below ground vegetables' are restricted to potatoes. All food produced in the study area is assumed to be evenly distributed for consumption among the local population of approximately 17,000 persons.

**External exposure calculations:** The local population was assumed to reside permanently in the area. Exposures were calculated on the basis of people remaining at their place of residence. Calculation of local collective dose commitment assumes that all exposed individuals are adults having the lifestyle patterns as indicated in Table 5-1(b).

### 5.2.4 Great Lakes (Regional) Population

This regional group consists of 38.8 million individuals living around three Great Lakes, Huron, Erie and Ontario, and who derive their drinking and washing water from these lakes. The amount of time they spend bathing, washing and swimming, estimated at 0.3% of the time, is similar to that of the local group. In estimating dose delivered from drinking water, the present population distribution of the 38.8 million people is as follows: 36,000 people in the area of the North Channel of Lake Huron, 2.38 million people on Lake Huron, 21.9 million persons on Lake Erie and 14.5 million persons on Lake Ontario.

In estimating the dose to the Great Lakes regional population, the commercial fish catch for each of the three Great Lakes downstream of the Serpent River system was estimated based upon commercial catch data from the 1970's. Concentrations of radionuclides in fish from each of these lakes were calculated. The catch was assumed to be consumed by the Great Lakes group to calculate the fish contribution to the regional dose, even though a high percentage of the commercial fish catch is exported out of the Great Lakes basin. If this were considered in the calculations, it would lower the dose per individual to the regional population although the total dose commitment derived from the Great Lakes basin would be the same.

Within the Great Lakes basin, no contributions to the regional dose from aquatic plants, such as wild rice and/or from mammals such as moose, are included as input to the model. No corrections are made for radionuclide removal in water treatment facilities.

### 5.2.5 North Atlantic Regional Group

The waters draining the reference tailings area pass through the Great Lakes and eventually discharge to the North Atlantic to mix with the surface waters of the North Atlantic. A population of 385 million persons was assumed to have access to the North

Atlantic coastline for recreational use. The dose to this group was from swimming, walking on the beach and sunning on the beach. No dose occurred to this group from drinking water from the North Atlantic, as seawater is not consumed.

The hydraulic model for the North Atlantic allows for the separation of surface and deep waters and the calculations of radionuclide concentrations in each of these different water masses. Surface water concentrations were used to determine the concentration of the radionuclides in the commercial fish and shellfish from the North Atlantic. The commercial fish catch for the North Atlantic was estimated at 16.8 million tonnes per year, and the consumed shellfish catch was estimated at 25% of this amount. The concentration factors used are shown in Table 4-1.

### 5.2.6 Global Population

Modeling results indicate that virtually all of the particulate material released from the reference tailing area will be deposited within an 80 km radius of the reference site. Radon gas is the only radionuclide expected to be transported beyond the 80 km radius. The Global population considered exposed to radon gas consists of 4 billion people in the northern hemisphere. For aquatic pathways, the global population includes all above population groups.

# 6.0 DOSIMETRY

## 6.1 Dosimetry Basis

Radioactive materials released to waters and the atmosphere will lead to human exposure through ingestion of water and foods and from direct exposure to contaminated shoreline and soils and water and air immersion. The more important exposure pathways and a general outline of dose calculations for the individual are shown in Figure 6-1 for aquatic pathways and Figure 6-2 for atmospheric routes.

Dosimetry calculations are based on ICRP-26 (1977), except that doses are expressed in terms of rem. The effective dose equivalent for individuals, $H_E$, is defined as:

$$H_E = \sum_T W_T \; H_T \qquad (0.1)$$

where $H_T$ = dose equivalent in tissue T;

$w_T$ = weighting factor for each tissue, representing the ratio of the stochastic risk from irradiation of the tissue, T, to that for the whole body when uniformly irradiated;

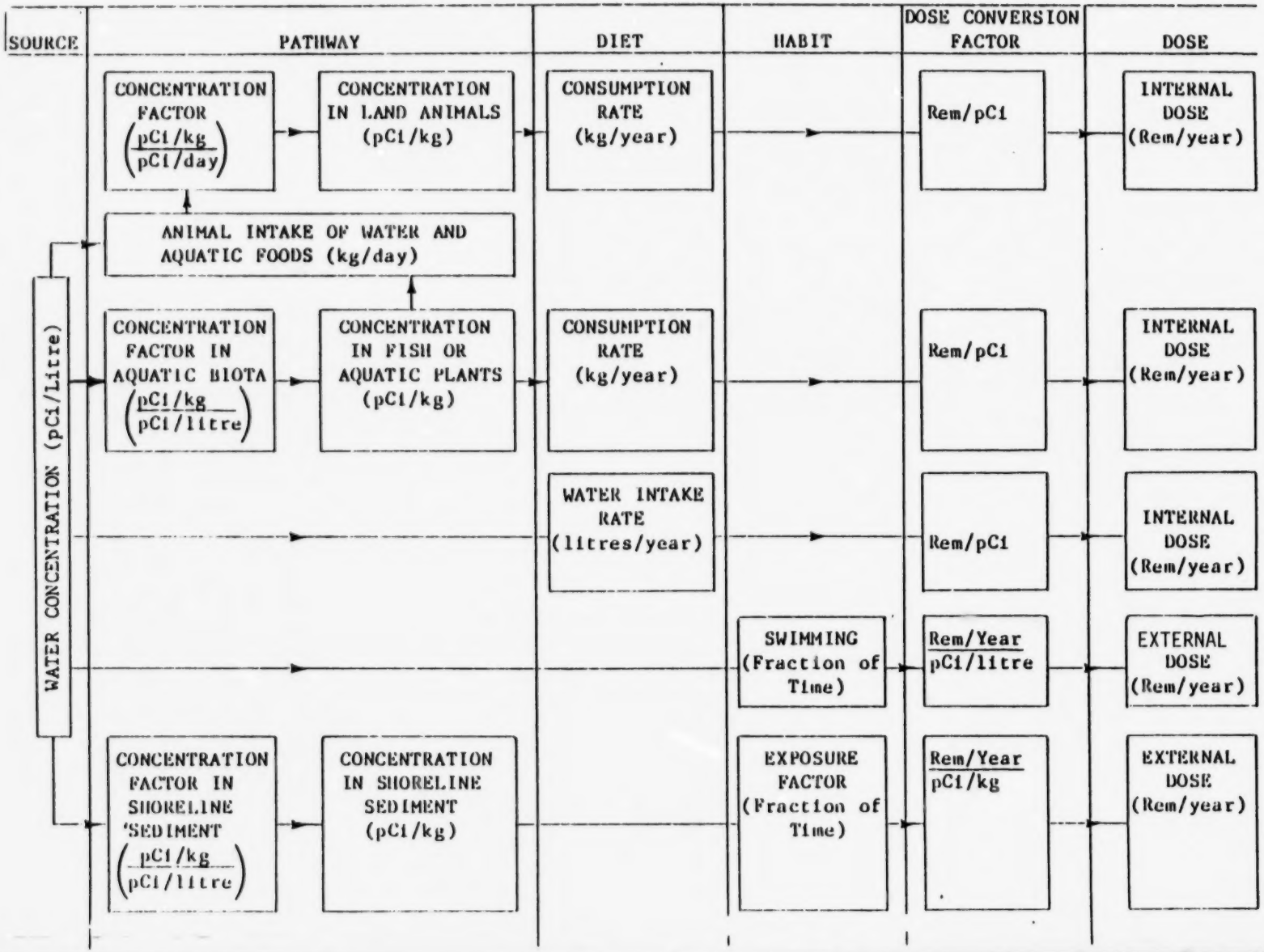
The weighting factors $W_T$ have been defined in ICRP Publication 26 for all body organs and tissues, except for skin, plus hereditary effects for the first two generations.

The collective effective dose equivalent, $S_E$, is given by:

$$S_E = \int_0^\infty H_E \; N(H_E) \; dH_E \qquad (0.2)$$

where $N(H_E)$ is the number of individuals receiving an effective equivalent in the range $H_E$ to $H_E + dH_E$.

FIGURE 6-1: EXPOSURE PATHWAYS AND INDIVIDUAL DOSE CALCULATIONS FOR RADIONUCLIDE RELEASES TO SURFACE WATER



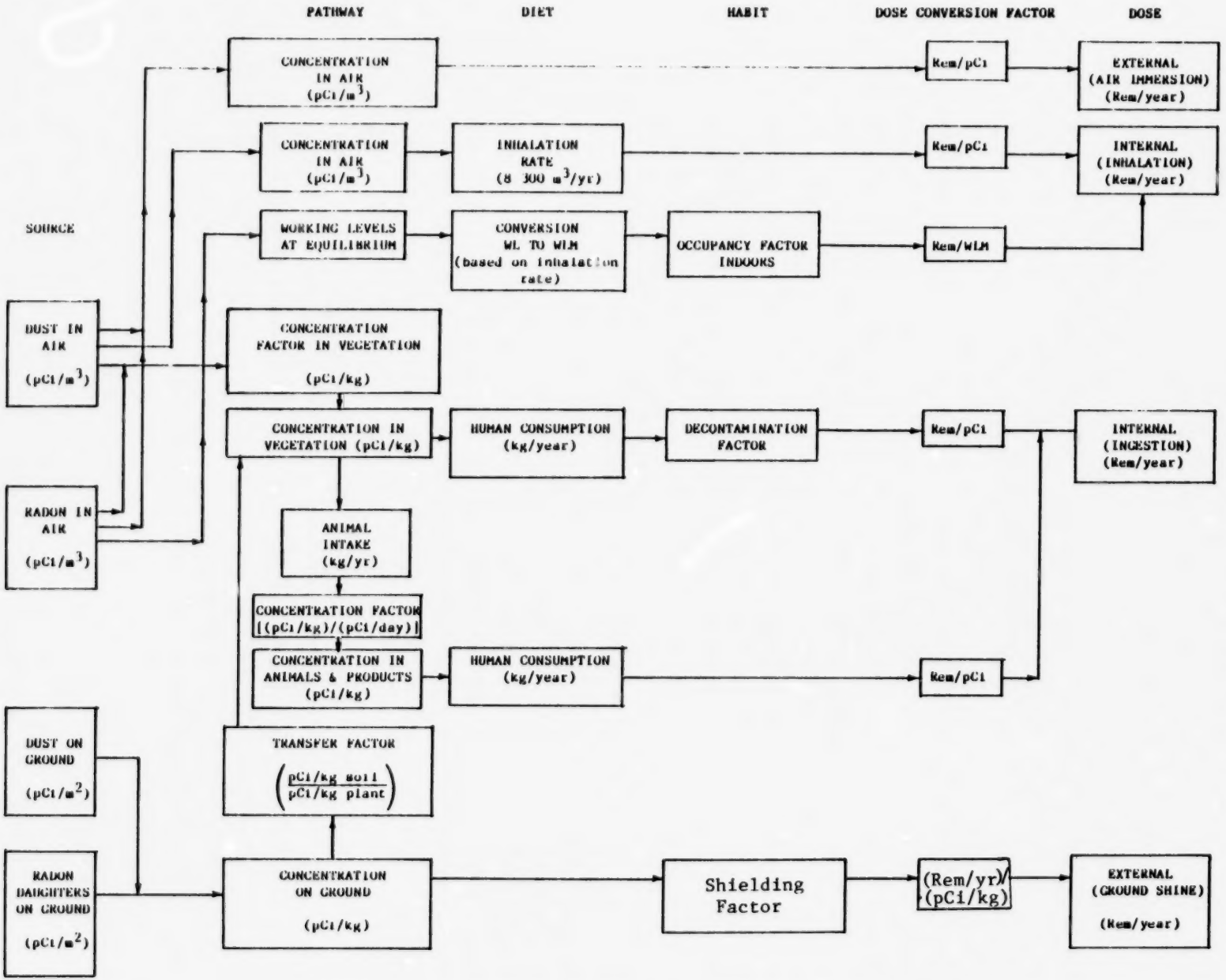



FIGURE 6-2: EXPOSURE PATHWAYS AND INDIVIDUAL DOSE CALCULATIONS FOR RADIONUCLIDE RELEASES TO THE ATMOSPHERE

The collective effective dose equivalent commitment, $S_E^C$, is obtained by integrating the collective effective dose equivalent rate (say, rem/year) over all time, ie.,

$$S_E^C = \int_0^\infty \dot{S}_E(t)\, dt \qquad (0.3)$$

If integration is limited in time, the resulting integral is called the incomplete collective effective dose equivalent commitment.

For internal exposures, $S_E^C$ is more conveniently represented as:

$$S_E^C = \bar{H}_E \int_0^\infty I.C(t)\, dt \qquad (0.4)$$

where I = Total intake rate of food, water, or air by the population (kg/year or $m^3$/year);

C(t) = Concentration of radionuclide in food, water, or air (pCi/kg or pCi/$m^3$);

$\bar{H}_E$ = population-averaged effective dose equivalent per unit of radioactivity intake (rem/pCi).

The quantity I.C (t) is the collective intake rate (pCi/year). $\bar{H}_E$ for the population is approximated by the 50-year integrated committed effective dose equivalent for adults, $H_{50,E}$, which is commonly tabulated for occupational exposures.

The incomplete collective effective dose equivalent commitment, which is the quantity evaluated in this study, is the sum of the effective dose equivalent commitments (integrated to a finite time T), received by all populations in all identified regions for all radionuclides and through all exposure pathways. To account for the risks from hereditary effects to populations beyond the first two generations, as well as fatal skin cancer, the total incomplete collective effective dose equivalent commitment, $S_y$, is calculated as:

$$S_y = S_E^C + 0.25\, S_{gonads}^C + 0.01\, S_{skin}^C \qquad (0.5)$$

The weighting factor for gonads is 0.25 (ICRP-26) and for skin 0.01.

## 6.2 Dose Conversion Factors

Dose conversion factors used in this study for external and internal exposure for each parent plus daughters in equilibrium are summarized in Table 6-1.

The dose factors for external exposure given for the radionuclides include contribution from relatively short-lived daughters with which they are in equilibrium. The dose factors for external exposure to contaminated shoreline sediment are labelled Individual-External-Beach for the Critical Group and Collective-External-Beach for the different population groups (units: rem/year per pCi/kg). They consider that exposed shoreline sediment is uniformly contaminated to some depth and include corrections for shore width; they are based upon the air gamma dose at 1 meter above sediment and are corrected to effective dose equivalent. The external dose conversion factor for contaminated water is labelled as swimming under the Critical Group and population group categories (rem/year per pCi/L). The skin dose is based upon the sum of photon and electron doses at 70 um below the body surface.

For internal exposure to radionuclides, the Committed Effective Dose Equivalent conversion factors are given for Individual-Internal for one-year old and adult of the Critical Group and for Collective-Internal-Adult for the population group. These factors are those calculated for intake by adults, integrated over a period of 50 years after uptake. Gonadal dose factors, available only for Ra-226 and Ra-228, are included as per equation 0.5.

Use of these dose conversion factors, together with the consumption rate of foods (internal exposure) and the exposure rate to contaminated sediment and water (external exposure) given previously, permit calculation of the internal and external dose rates (eg., rem/year) for the Critical Group and the different population groups (local, regional, oceanic, global). Integration of the effective dose equivalent commitment rate from all radionuclides through all exposure pathways to the time T gives the incomplete collective effective dose commitment for that population. This quantity is hereafter abbreviated and called the cumulative population dose, the population dose, or the population dose to time T.

TABLE 6-I: SUMMARY OF DOSE CONVERSION FACTORS FOR DOSIMETRY MODEL

| | Dose Conversion Factors | | | | | | |
|---|---|---|---|---|---|---|---|
| | Individual-Internal | | Individual-External | | Collective-Internal | Collective-External | |
| | 1 Year | Adult | Swim | Beach | Adult | Swim | Beach |
| | Rem/pCi Ingested | | Rem/a per pCi/kg | | Rem/pci Ingested | Rem/a per pCi/kg | |
| U-238 | $4.8 \times 10^{-7}$ | .23E-06 | .46E-06 | .11E-06 | .23E-06 | .46E-06 | .14E-06 |
| U-234 | $5.2 \times 10^{-7}$ | .26E-06 | .23E-07 | .30E-08 | .26E-06 | .29E-06 | .38E-08 |
| Th-230 | $2.0 \times 10^{-4}$ | .54E-06 | .22E-07 | .32E-08 | .54E-06 | .28E-07 | .40E-08 |
| Ra-226 | $4.4 \times 10^{-6}$ | .11E-05 | .26E-04 | .12E-04 | .14E-05 | .33E-04 | .15E-04 |
| Pb-210 | $2.6 \times 10^{-5}$ | .50E-05 | .98E-07 | .12E-07 | .50E-05 | .12E-06 | .15E-07 |
| Po-210 | $3.0 \times 10^{-6}$ | .16E-05 | .13E-09 | .60E-10 | .16E-05 | .16E-09 | .75E-10 |
| Th-232 | $6.7 \times 10^{-4}$ | .27E-05 | .19E-07 | .15E-04 | .27E-05 | .24E-09 | .19E-04 |
| Ra-228 | $1.1 \times 10^{-9}$ | .12E-05 | .14E-04 | .15E-04 | .18E-05 | .18E-04 | .19E-04 |
| Th-228 | $3.6 \times 10^{-4}$ | .38E-06 | .24E-04 | .93E-05 | .38E-06 | .30E-04 | .12E-04 |

Global Atmospheric doses from Radon-222. Dose conversion factor: 0.09 man-rem/Ci released per year (0.025 man-sv/TBq). Based on 4 billion inhabitants in Northern hemisphere and conversion factor includes all pathways.

## 7.0 RADIATION DOSE IMPACT ESTIMATES

This section presents the dose impact estimates produced by use of the Loading-Dosimetry model. Estimates are given for critical group dose rate trends, and for cumulative global collective committed doses. A separate set of estimates is given for each of the six tailings management cases studied.

**Caution.** The dose impact estimates do not address any specific site, either existing or projected. They are estimates only, made for an hypothetical site placed in a synthetic environment. The tailings management cases are simplified and idealized. The dose impact estimates are intended only to show the expected trends which would result from performing certain operations on an hypothetical mass of tailings.

### 7.1 Porous Dam - Cases 1 and 4

#### 7.1.1 Case 1: Porous Dam - Untreated Tailings

**Critical Group.** The dose rate experienced by the most highly exposed individual within the critical group, as a function of time, strongly reflects the release rates of radionuclides. Figure 7-1(a) shows the dose received by the most highly exposed member of the critical group from all pathways. The initial rise in the dose rate curve reflects the flushing of mill derived pore water and its dilution in the receiving lake. After about 2.5 years, equilibrium levels of radionuclides are established in the receiving lake water, biota and sediments. At this time, dose rates from atmospheric pathways are about 5% of the aqueous derived dose rates. Atmospheric contributions drop to about 2% at 150 years.

At some point between 150 and 175 years, the tailings pore water becomes acidic, and flushes out many of the hydroxides of radionuclides such as thorium. This causes an increase in the level of certain radionuclides and hydrogen ions in the receiving lake and the pH of its water begins to drop. Increased radionuclide concentrations in the receiving lake cause critical group dose rates to rise. At some point between 175 and 200 years, the pH of the receiving lake drops below 4.5 and fish from that water body are assumed to disappear from the lake and hence from the diet of the critical group. Radionuclides ingested in fish flesh constitute a high percentage of critical group dose

FIGURE 7-1(a): DOSE RATE TO THE MOST HIGHLY EXPOSED INDIVIDUAL

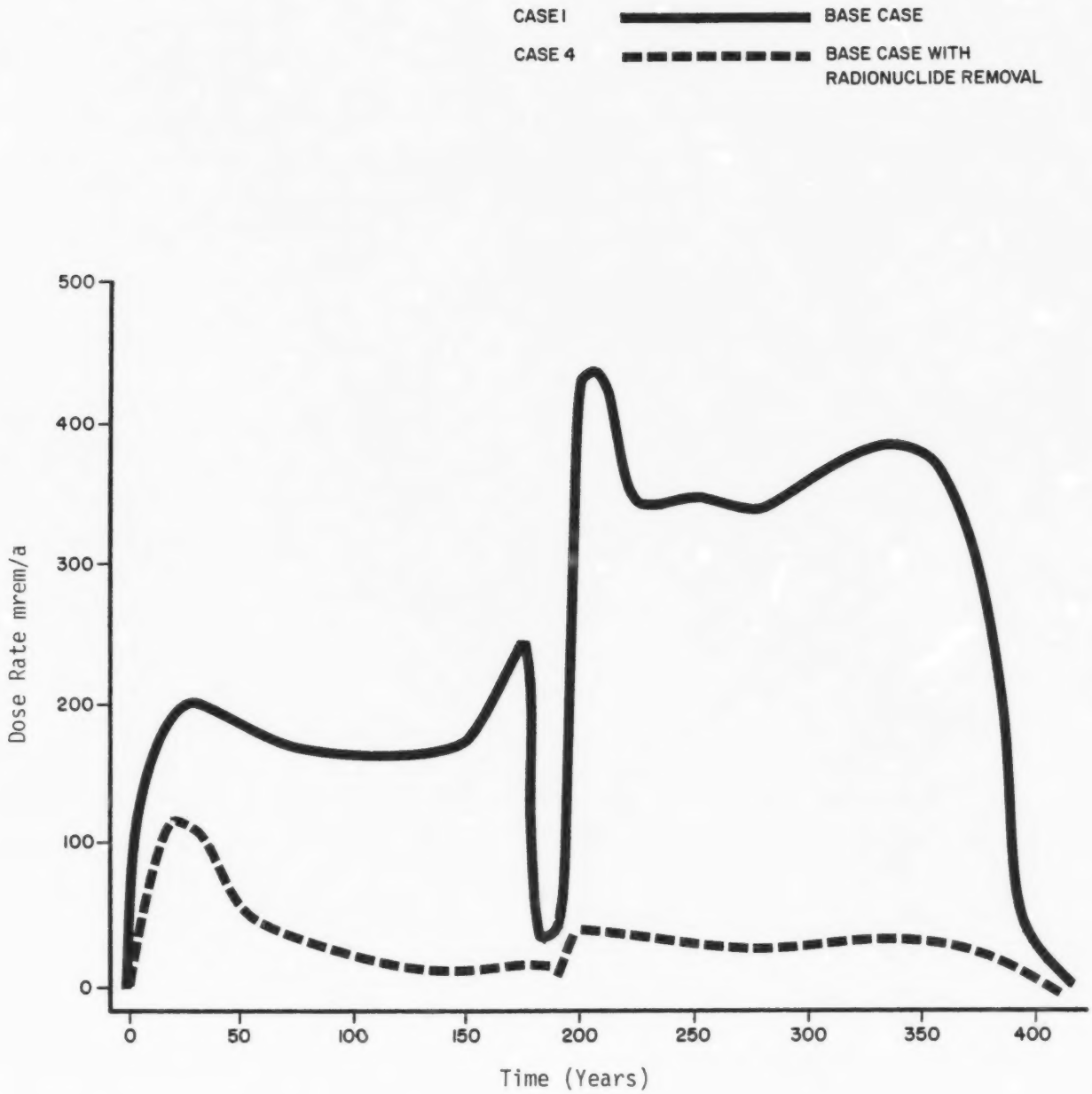


FIGURE 7-1(b): COLLECTIVE DOSE COMMITMENT BASE CASE

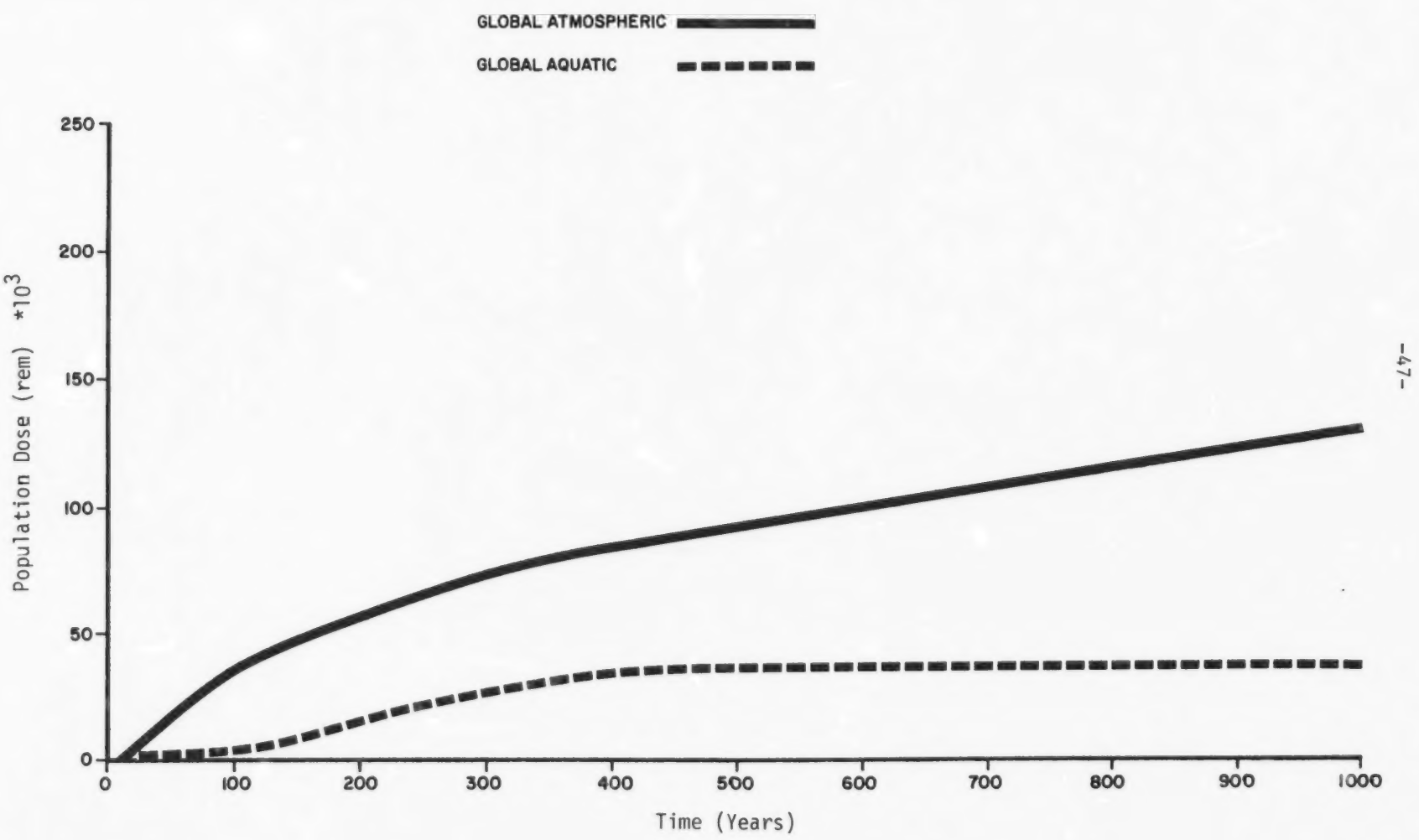
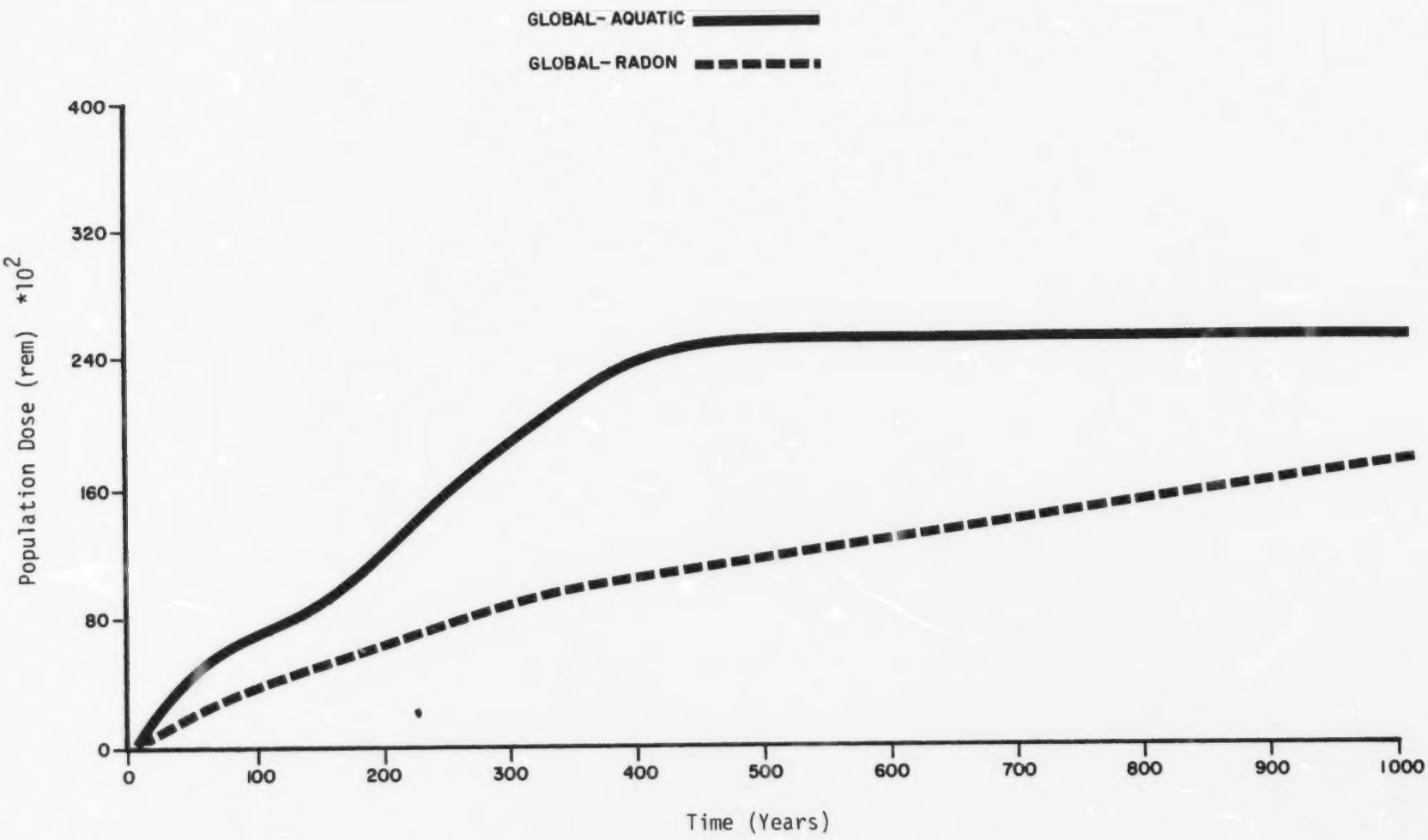


FIGURE 7-1(c): POPULATION DOSE COMMITMENT CASE 4



rates, so the dose rate drops sharply. Drinking water and bathing water is still assumed to be drawn from the receiving lake. There is still a small dose from radon and dust from the tailings.

About 200 years after closeout, most of the available pyrite in the unsaturated zone of the tailings is calculated to have been oxidized. Acid loading to the receiving lake drops, allowing an increase in pH. When the pH rises to above 4.5, fish from upstream watershed areas recolonize the receiving lake. These fish again become an important part of the diet of the critical group, and dose rates increase. The pH recovers to near pre-acidification pH about 225 years after closeout. The oxidation of pyrite within the saturated zone continues slowly, resulting in a weakly acidic seepage water. This allows gypsum in the tailings to dissolve. As the pore water pH increases further, jarosite dissolves. These mechanisms release radionuclides to the pore water, seepage and hence the receiving lake. Critical group dose rates increase. Dose rate fluctuates slightly between 225 and 275 years, then slowly rises reflecting jarosite instability. Finally, it tails off when all the gypsum and jarosite have been leached from the tailings mass.

**Collective Committed Doses.** The pattern of exposure to individuals living further downstream and at greater distances along the transfer pathways is smoothed out considerably from that of the critical group. Figure 7-1(b) shows the cumulative global population dose commitments from aquatic and atmospheric pathways. (Populations are defined in Section 5 of this report.) The global dose commitment from aquatic pathways includes the sum of these three aquatic pathways. The global radon component of the incomplete collective dose is about the same as the aquatic dose to the North Atlantic rim population. The aquatic pathway dose for the Case 1 is close to complete at 1000 years. The global radon contribution to the collective dose continues at a level close to the regional background. It will remain there until the tailings mass becomes covered through natural events.

### 7.1.2 Case 4: Porous Dam - Radionuclides Extraction From Tailings

The broken line on Figure 7-1(a) shows the trend of critical group dose rates. Dose rates peak after 20-25 years. This peak reflects the initial flush of tailings pore water into the receiving lake. This pore water contains radium daughters (principally lead-210) that are at a higher level than secular equilibrium with the radium in the tailings. As the pore

water is flushed and as lead-210 decays in the tailings, the concentration of radionuclides drops off and approaches secular equilibrium with the remaining radium. Acid production and neutralization reactions occur as in the base case, but because of the much lower mass of radionuclides in the tailings, the dose to the critical group is at a much lower level.

Figure 7-1(c) shows global collective committed doses from atmospheric and aquatic pathways. Atmospheric releases of fugitive dust activity and radon gas are lower in proportion to the reduction in thorium and radium.

## 7.2 Vegetation Cover on Tailings - Cases 2 and 5

### 7.2.1 Vegetation Cover - Porous Dam - Untreated Tailings

The effects of the vegetation cover on radionuclide transport are discussed in subsection 3.3 of this report.

**Critical Group.** Figure 7-2(a) shows the trend predicted for critical group composite dose rates. There is no contribution from atmospheric dust. The dose contribution from radon release is greatest at closeout; it then drops slowly as radium is dissolved from the unsaturated zone and moved into the deeper saturated zone. The dose contribution to the critical group from waterborne radionuclides follows a similar pattern to that of Case 1. There are, however, differences in levels and timing. Dose rates rise with the initial flush of mill-derived tailings pore water. The larger unsaturated volume of tailings results in a greater amount of acid being produced in a shorter period of time from the same mass of tailings. The vegetation also results in a lower flushing rate of the tailings. Hence there is a lower mass transfer of radionuclides to the receiving lake. The effect of these factors is to reduce critical group dose rates and shorten the time for the tailings seepage to become acidic. The pH in the receiving lake begins to drop below pH 4.5 after about 150 years, 25 years earlier than Case 1. The dose to the critical group thus begins to drop earlier as fish disappears from the diet. The slower flushing rate lowers the general level of critical group dose rates compared with Case 1. The total mass of radionuclides leached is comparable to Case 1 but, because of the lower hydraulic flushing rate, the process continues for 50 years longer.

FIGURE 7-2(a): DOSE RATE TO THE MOST HIGHLY EXPOSED INDIVIDUAL

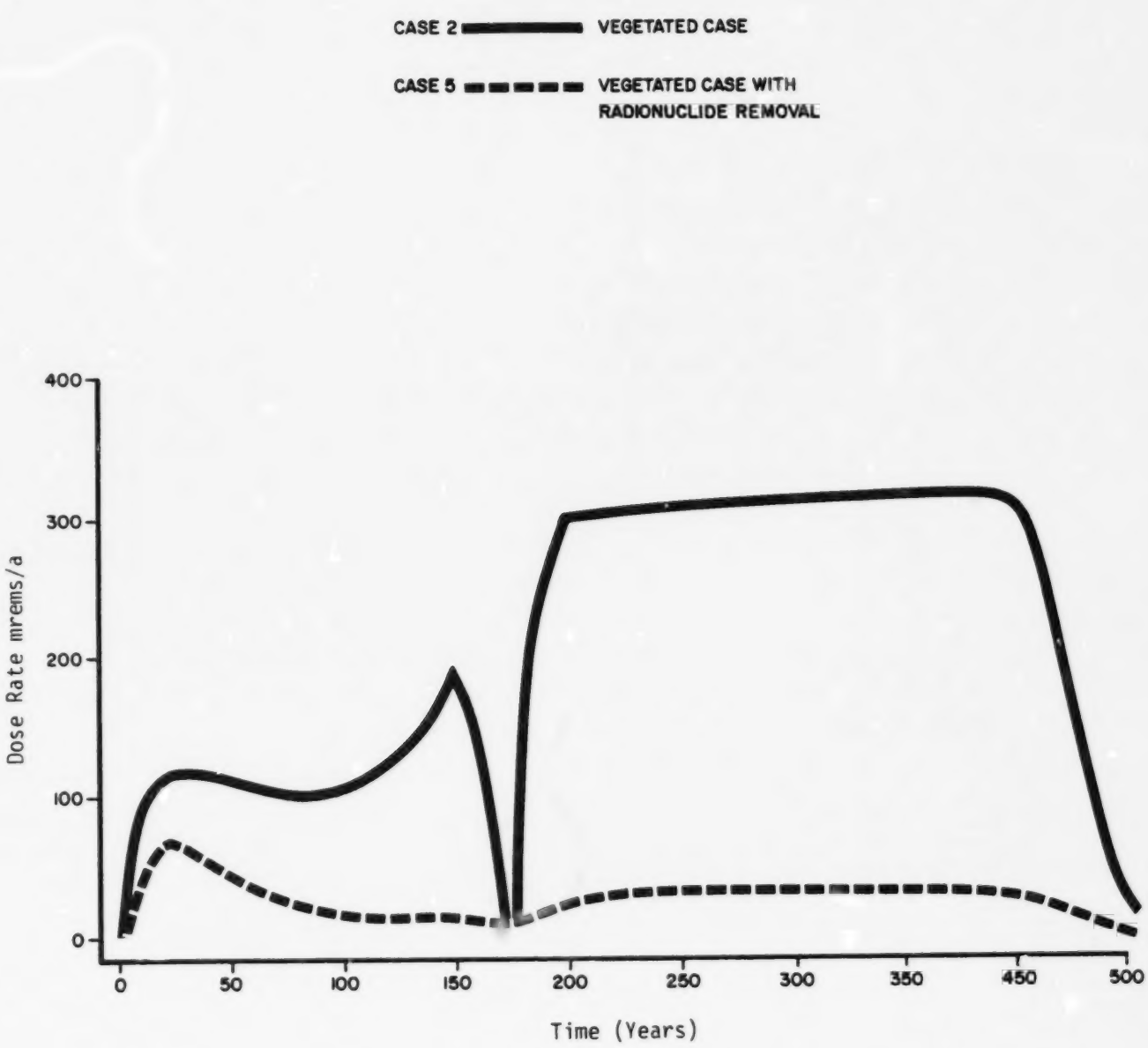


FIGURE 7-2(b): POPULATION DOSE COMMITMENT CASE 2

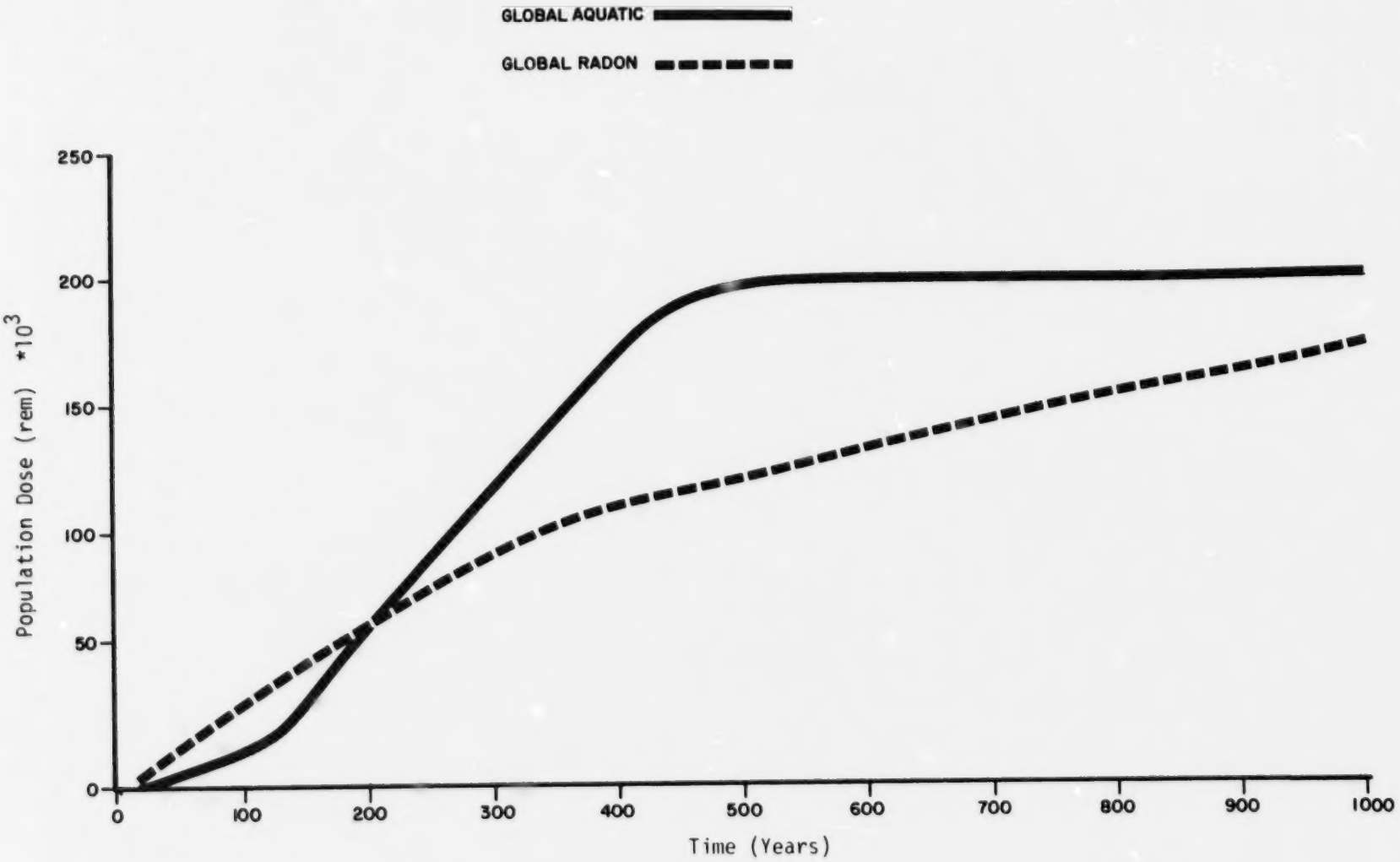
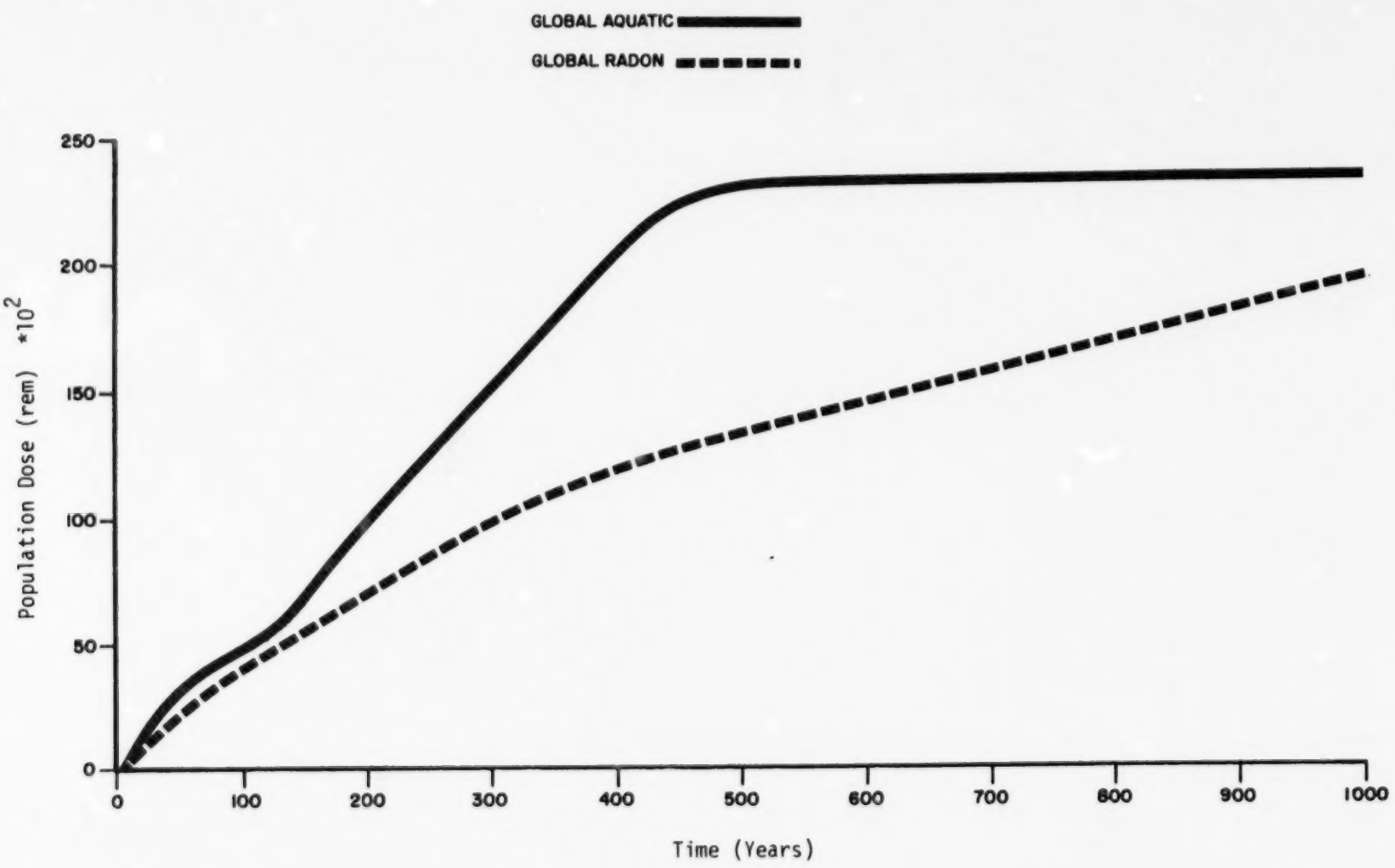


FIGURE 7-2(c): POPULATION DOSE COMMITMENT CASE 5



**Collective Committed Doses.** For Case 2, these are shown in Figure 7-2(b). The global aquatic collective dose commitment is comprised of the collective dose to inhabitants of the local watershed, the Great Lakes basin and the North Atlantic rim. The global atmospheric collective dose commitment is soley from radon and is calculated as a total northern hemisphere dose.

### 7.2.2 Case 5: Porous Dam - Vegetation Cover - Radionuclides Extracted from Tailings

**Critical Group.** There is an initial peak in dose rates reflecting the initial pore water flush. This is followed by a gradual drop and a slight rise reflecting the initial acid flush of the tailngs. Following this, there is a slight drop while fish are absent from the diet of the critical group. As the pH of the receiving lake recovers following the complete oxidation of the pyrite in the unsaturated zone, fish again become an important component in critical group exposure. After about 400 years, most of the potentially water soluble radionuclides have been leached from the tailings mass and the dose rate to the critical group begins to drop off. See Figure 7-2(a), broken line.

Collective committed doses arising from Case 5 are shown in Figure 7-2(c). The collective dose commitment from Case 5 is about 10% of that produced by Case 2.

## 7.3 Low Permeability Dam Option - Cases 3 and 6

The effects of a low permeability dam on radionuclide transport are described in Section 3.3 of this report.

### 7.3.1 Case 3 - Low Permeability Dam - No Vegetation - Untreated Tailings

**Critical Group.** Figure 7-3(a) shows the trends in the critical group dose rates. The radionuclide release rate from the tailings is slow and constant over a period of about 6000 years. The concentrations of radionuclides in the receiving environment rise steadily but reach no plateau. The rate of release is controlled soley by the hydraulic flushing rate and the solubility of calcium sulfate and jarosite. After these materials have been dissolved and washed from the tailings mass, the concentrations in the downstream receiving environment drop off and approach natural background levels. The

FIGURE 7-3(a): DOSE RATE TO THE MOST HIGHLY EXPOSED INDIVIDUAL

CASE 3 ——— LOW PERMEABILITY

CASE 6 - - - - - LOW PERMEABILITY DAM WITH RADIONUCLIDE REMOVAL

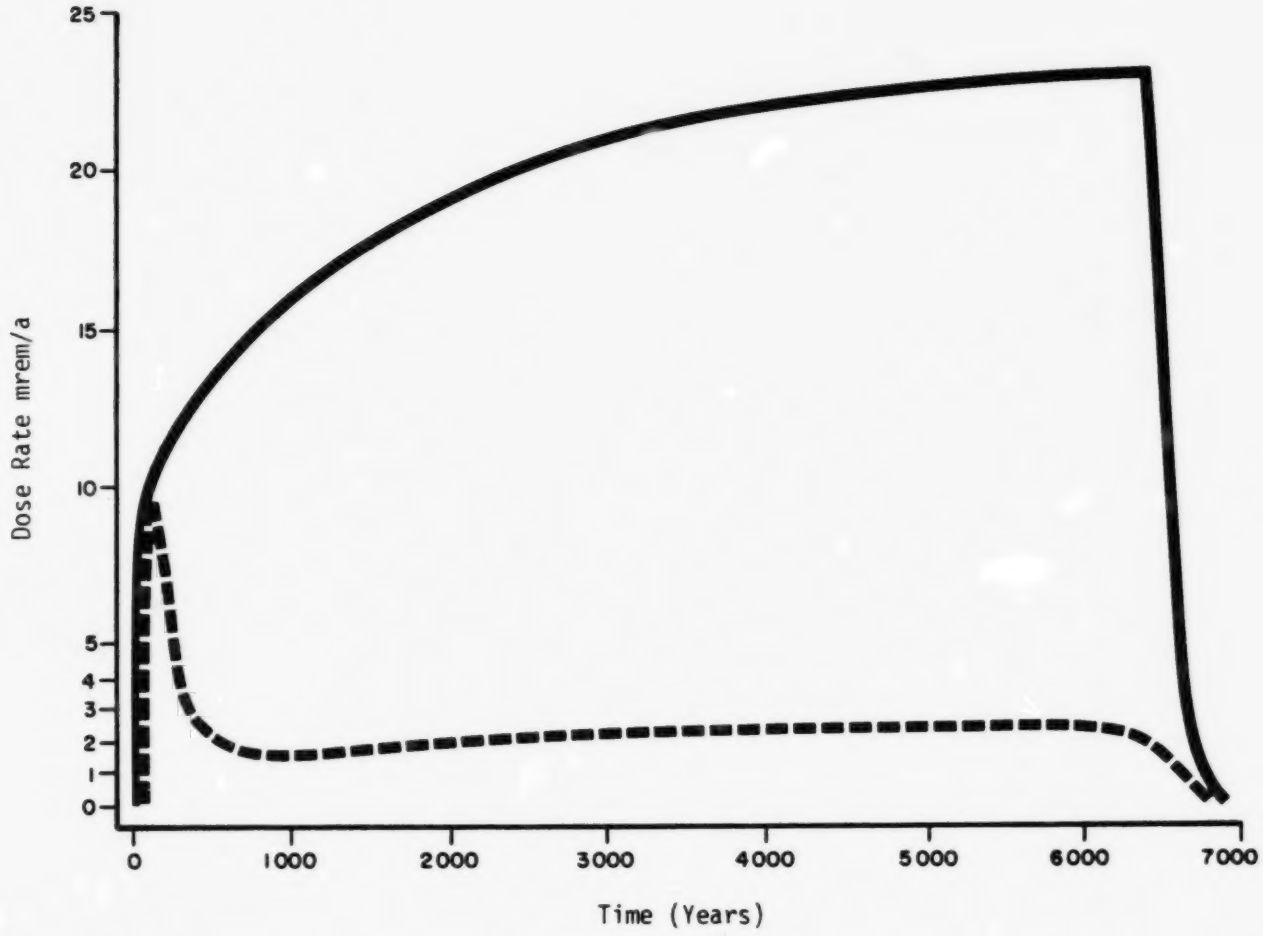


FIGURE 7-3(b): POPULATION DOSE COMMITMENT CASE 3

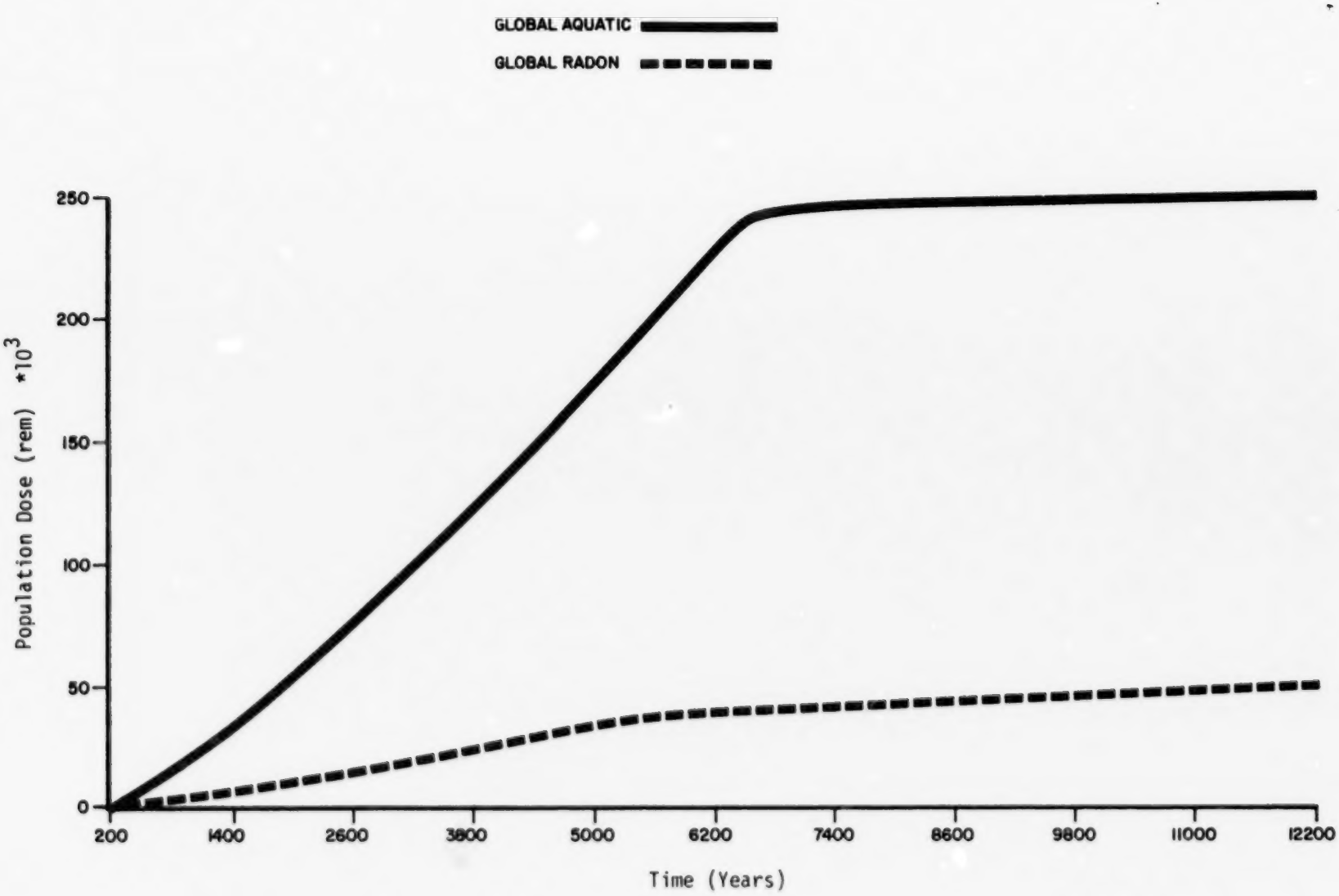
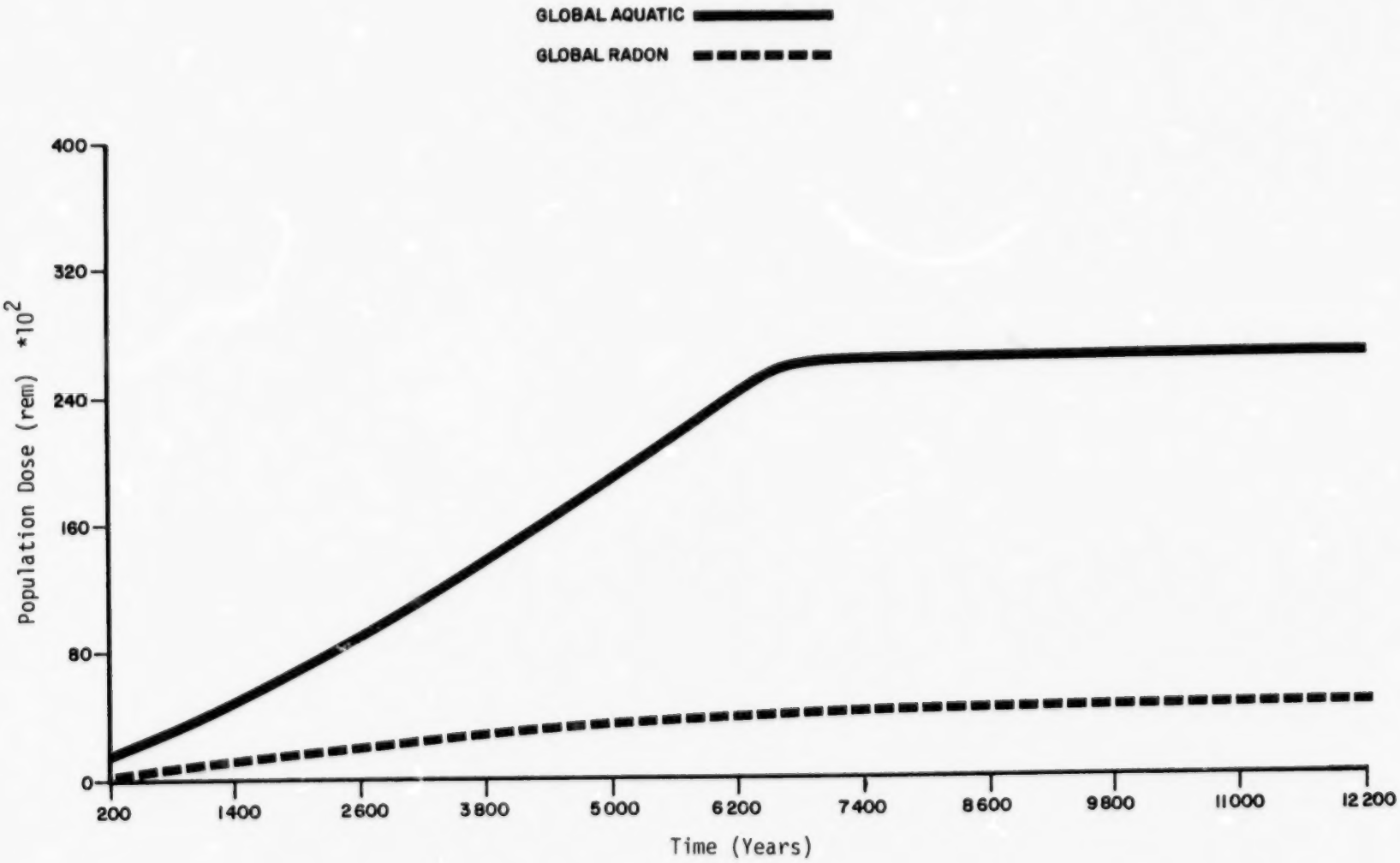


FIGURE 7-3(c): POPULATION DOSE COMMITMENT CASE 6



maximum dose rate from atmospheric pathways (radon) to the critical group in this management case is on the order of 0.05 mrem/a. This low level cannot be discerned on the scale of Figure 7-3(a).

**Collective Dose Commitment.** (See Figure 7-3(b)). The collective dose commitment shows a slow and steady increase reflecting the dispersion and slow buildup of radionuclides in the environment. The global radon contribution to collective dose is much less than the aquatic contribution. This is because the saturated tailings surface greatly impedes radon diffusion to atmosphere. Radon decay within the tailings mass is, therefore, much more significant than in the porous dam strategies.

**Case 6: Low Permeability Dam - No Vegetation - Radionuclides Extracted From Tailings**

**Critical Group.** See Figure 7-3(a), broken line. The initial dose rate peak results from the flushing of mill process pore water in the tailings. Its sharp drop-off is a reflection of the lead-210 decay in the tailings themselves. After several hundred years, residual lead-210 has either been flushed out of the tailings system, or has decayed to very low levels. Leachate activity, and hence dose rate to the critical group, shows the same slow rise as when the thorium and radium were not extracted. Because of the low rate of oxygen penetration into the tailings, the reference tailings in Case 6 do not go acidic within the 10,000-year reference period.

**Collective Dose Commitments.** Figure 7-3(c) shows that extraction of thorium and radium from the tailings reduces the global dose commitments by a factor of about 10, compared with Case 3.

## 8.0 SENSITIVITY ANALYSIS

A sensitivity analysis was carried out using the developed Loading-Dosimetry model. Being a diagnostic model, the Loading-Dosimetry model allows ranges of values to be placed on the input variables.

The sensitivity analysis had two components:

- Analysis of the effects, on estimated dose impact, caused by changing some of the model variables.
- Analysis of the magnitudes of individual doses making up the collective committed dose total for a given population.

Results of the analyses are discussed below, and are summarized in Tables 8-1 and 8-2.

### 8.1 Changes in Model Variables

**Important Variables.** In this case, 'variable' means any numerical coefficient or parameter used in the model. Variables include such entities as gas diffusion rates, dose conversion factors, and adsorption coefficients.

A few of these variables such as the radioactive decay constants are relatively well known and can be specified with a high degree of accuracy. Other variables such as bioconcentration factors or atmospheric dispersion may be less well definable and/or highly site-specific.

**Effects of Changing Variables.** Table 8-1 presents a series of variables from each of the four major model components, that were varied as part of the sensitivity analysis. The table shows the degree of variable variation and the resultant effect on dose impact.

A review of Table 8-1 shows that the end result, either expressed as dose to the critical group or as a collective dose commitment, is more sensitive to changes in certain variables rather than others. For example, in the source model, if the adsorption coefficient of Ra-226, Po-210 and Pb-210 is increased ten times, this has the result of

TABLE 8-1: CASE 1 SENSITIVITY ANALYSIS - VARIABLES
- Selected Results -

| Model Component | Variable | Range | Critical Group % of Case 1 Dose Rates | Collective Dose Commitment % of Case 1 Dose |
|---|---|---|---|---|
| Whole Model | All Case 1 variables | As specified | 100% | 100% |
| Source | Gypsum Solubility | Reduce solubility to .1 | 57% | 89% |
| | Ra, Pb, Po Adsorption Coefficient (Kd) | Increase 10X | 113% | 87% |
| Transport | Water Column Adsorption Coefficient | Increase 5X<br>Decrease 5X | 89%<br>113% | 24%<br>287% |
| | Water Column Particle Settling Velocity | Increase 5X | 71% | 9.4% |
| Ecosystem Partitioning | Bioconcentration Factor in Fish all Radionuclides | Reduce by 2X | 65% | 65% |
| | Human Water Intake | Reduce by 2X | 97% | 86% |
| Dose to Man | Th-230 Dose Conversion Factor | Reduce by 3X | 100% | 100% |
| | Ra-226 Dose Conversion Factor | Reduce by 5X | 88% | 93% |
| | Pb-210 Dose Conversion Factor | Reduce by 5X | 45% | 72% |

holding back these elements and resulting in a slower initial release. However, when the tailing mass goes acidic, there is a much larger mass of radium, polonium and lead in the tailing mass available for release. The model 'assumes' that all of the lead and polonium not physically entrapped in the gypsum matrix is present as a lead or polonium hydroxide. When the tailings pore water goes acidic, these hydroxides become soluble and are washed out into the receiving lake. As a consequence, the peak in critical group dose rate is delayed, but heightened at the peak. The lower levels prior to and following the release peak mean that a higher percentage of polonium and lead daughters originating from radon decay themselves decay to stable lead in the tailing mass. They do not reach the open environment where they can contribute to individual or collective dose.

**Collective Doses.** The model calculates concentrations of radionuclides in water and air to extremely low levels. Beyond a short distance from the source, concentrations drop off to levels that are not discernible from background and hence cannot be confirmed by monitoring. These levels, which are a small fraction of background, contribute a calculable but non-verifiable increment of dose upon background. We investigated the effects of curtailing collective dose commitment levels when dose rates to individuals fell below preselected levels. These levels were 1 nanorem/a, 1 microrem/a, 100 microrem/a and 1 millirem/a. They are known as the 'dose rate truncation levels'.

Table 8-2 presents the incomplete collective effective dose equivalent commitment as a function of dose commitment truncation. Doses are integrated over a period of 1000 years for the porous dam and vegetation cases and 10,000 years for the low permeability dam cases.

The table indicates that the majority of the collective dose is delivered at individual dose rates of less than 1 microrem/a. Taking the ICRP recommended mortality risk factor for radiation-induced cancer, this corresponds to an average individual risk factor of about $10^{-10}$ per year. The collective dose contribution at these very low levels is approximately equally split between atmospheric (radon) pathways and aquatic pathways for Cases 1, 2, 4 and 5. The collective dose commitment contribution for Cases 3 and 6 is almost entirely from aquatic pathways. Collective dose commitment delivered at individual doses above the 100 microrem/a cutoff is derived almost entirely from the aquatic pathway.

TABLE 8-2: SENSITIVITY ANALYSIS - DOSE RATE TRUNCATION
GLOBAL COLLECTIVE DOSE COMMITMENT AS A
FUNCTION OF DOSE RATE TRUNCATION LEVELS
(Dose Commitments in man-rem from all atmospheric and aquatic pathways)

| Tailings Management Method | Individual Dose Rate Truncation Level | | | | |
|---|---|---|---|---|---|
| | 1 mrem/a | 100 urem/a | 1 urem/a | 1 nrem/a | No Cutoff |
| Case 1 Porous Dam | $2.74 \times 10^4$ | $2.89 \times 10^4$ | $1.31 \times 10^5$ | $3.64 \times 10^5$ | $3.64 \times 10^5$ |
| Case 2 Vegetation Cover | $2.57 \times 10^4$ | $2.67 \times 10^4$ | $1.0 \times 10^5$ | $4.04 \times 10^5$ | $4.04 \times 10^5$ |
| Case 3 Low Permeability Dam | 0 | 0 | $2.9 \times 10^3$ | $2.51 \times 10^5$ | $2.51 \times 10^5$ |
| Case 4 Porous Dam - treated tailings | $1.25 \times 10^3$ | $4.02 \times 10^3$ | $8.15 \times 10^3$ | $4.84 \times 10^4$ | $4.84 \times 10^4$ |
| Case 5 Vegetation Cover - treated tailings | $5 \times 10^2$ | $3.42 \times 10^3$ | $5.69 \times 10^3$ | $4.68 \times 10^4$ | $4.68 \times 10^4$ |
| Case 6 Low Permeability Dam - treated tailings | 0 | 0 | $3.1 \times 10^3$ | $2.90 \times 10^4$ | $2.90 \times 10^4$ |

## 9.0 GLOSSARY OF TERMS

| | |
|---|---|
| ALARA: | As low as reasonably achievable (Social and Economic factors considered). A philosophy employed in reducing dose impacts embodying a cost-benefit approach to dose reduction. |
| Alluvial: | pertaining to or composed of earth deposited by water. |
| Close Out: | That point in time at which a tailings facility can be left in a passive maintenance condition. |
| Compartments: | a real or imaginary enclosure. Modeling term denoting artificially limited portion of a contiguous path transporting the commodity of interest. |
| Critical Group: | a collection of human beings whose dose commitment is maximized from a given hazardous source. |
| (D): | the proportionality constant between the flux of material passing across any arbitrary plane due to random dispersive processes and the gradient of concentration perpendicular to the plane measured at the plane. |
| Elution: | extraction of one material from another using a liquid. |
| Emanation Coefficient: | a factor used to derive the rate at which radon gas is given off by certain radioactive materials. |
| Goethite: | a yellow, red or dark brown mineral, chemical formula Fe0(OH). Found naturally in radiating fibrous aggregates. |
| Hydraulic Flushing Time | volume of water in a waterbody or water containing system, divided by the flow rate |

Jarosite: a hydrous sulphate of iron and potassium, occurring massive or in brown or yellow crystals: $KFe_3(SO_4)_2(OH)_6$

Nuclide: a nuclear species as marked by the atomic number and mass number.

Pachacas: process leaching containers in a uranium mill. May contain all or part of crushed ore, and/or extracts from ore.

Radionuclide: a radioactive nuclide.

Residence Half-Life: the time during which half of the quantity of a material remains in a given zone.

Secular Equilibrium: a state in a decay chain where the activity of a daughter radionuclide is a linear function of the activity of the parent.

Soil Horizon: a layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical and biological properties or characteristics such as colour, structure, texture, consistency, amount of organic matter and degree of acidity or alkalinity.

Specific Activity: the intensity of a radioactive source - of either a given pure radioisotope, of a given radioisotope in a sample, or of various radioisotopes in a sample. Expressed as activity (Ci or Bq) per unit mass or volume.

Spillway: a passageway in the retaining dam, to release the surplus water from the tailings surface.

Surficial Sediments: solid materials deposited at the bottom of a waterbody and in close contact with the waterbody.

| | |
|---|---|
| Transpiration: | a collective term for water transpired by vegetation and/or that evaporated from the soil. |
| WL: | Working Level. Term used in occupational radiation safety to define the airborne concentration of alpha-emitting radionuclides. Equivalent to 100 pCi/l of radon in air, in equilibrium with its daughters. |
| Water Column: | a hypothetical entity used in modeling. It is the representation of the vertical extent and characteristics of water, present usually in a waterbody. |

POOR

QUALITY

ORIGINAL